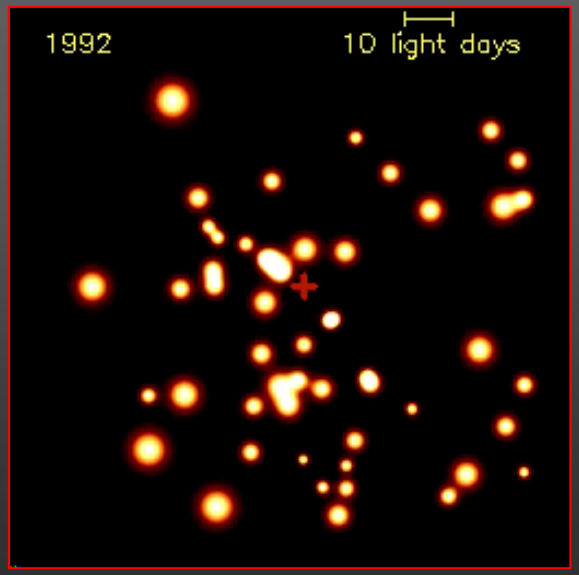
SgrA* at the Center of the Milky Way

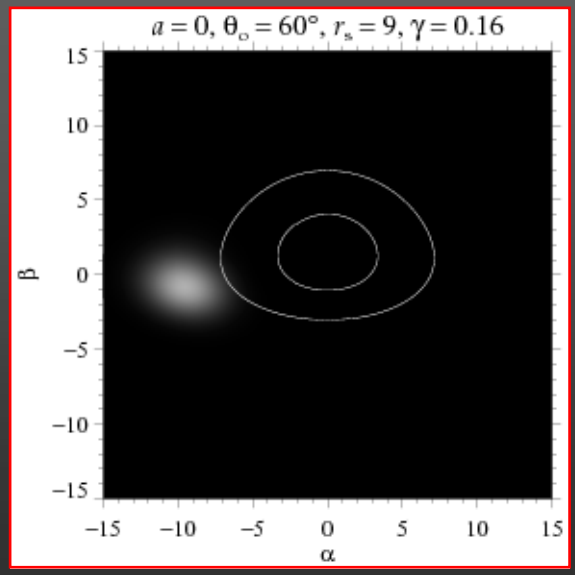
Observing the X- and γ-ray Sky

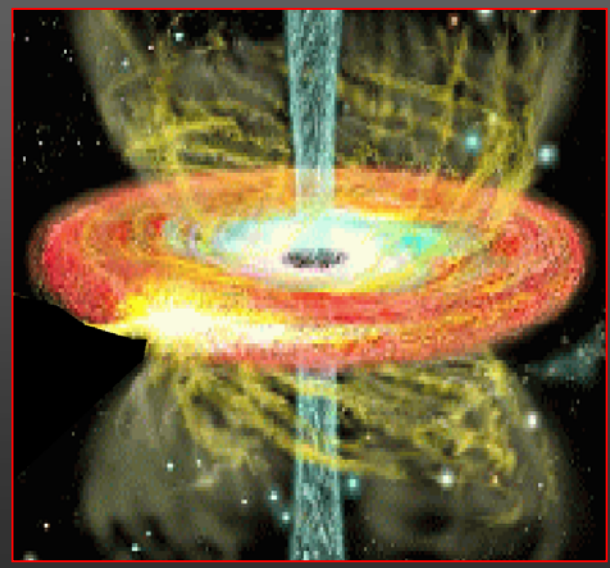
Astrophysical Spring School, April 2006

Andreas Eckart

I.Physikalisches Institut der Universität zu Köln







- I.Part

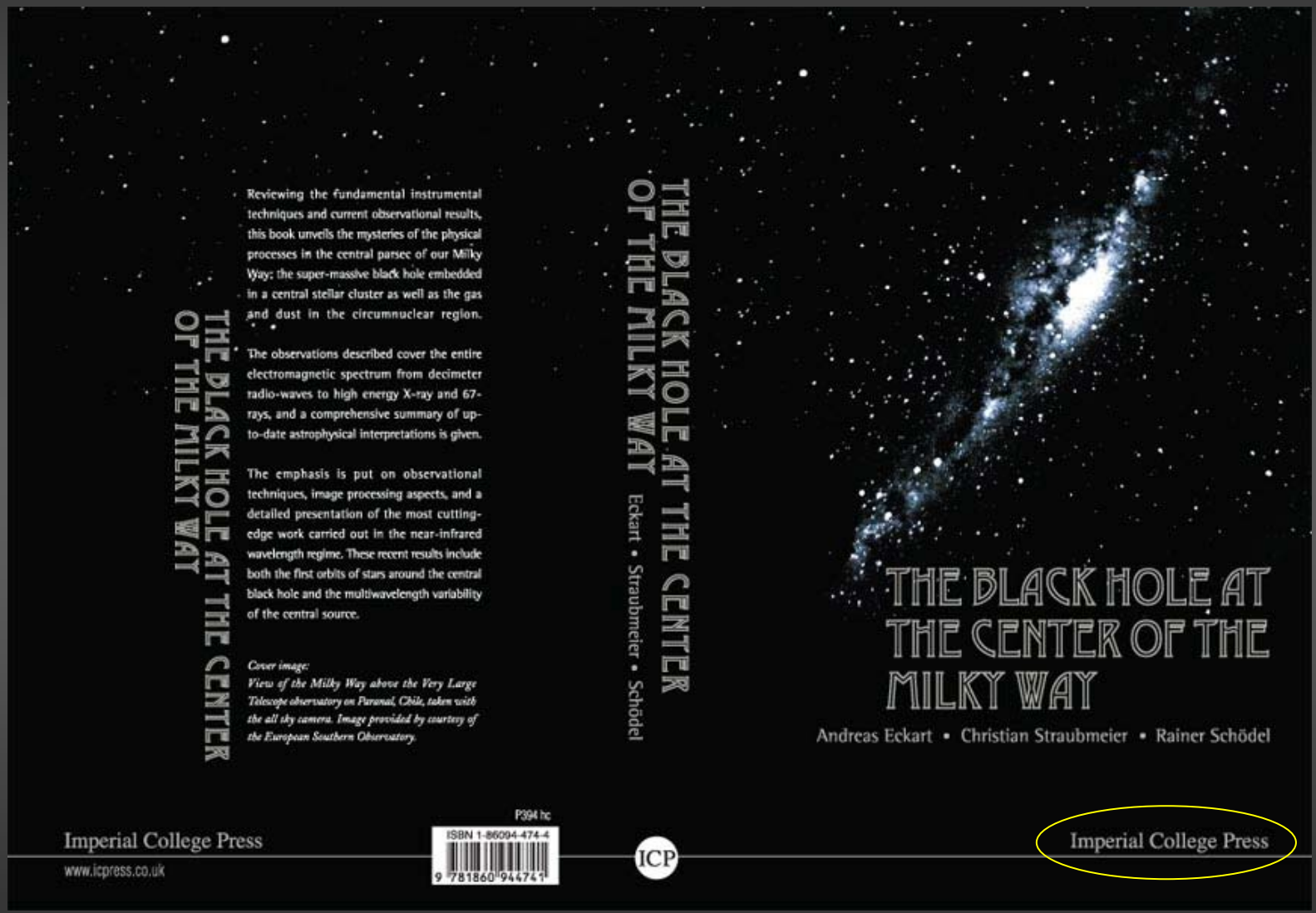
  Imaging: direct, speckle, adaptive optics
  Astrometry: relative positions, radio-link
  Spectroscopy: stellar populations
  Proper motions, radial velocities
  Kinematics of the central stellar cluster
  Derivation of the enclosed mass
  Enclosed mass and structure of the central mass distribution: compact mass and stellar cusp
  Stellar orbits: orbital elements,

- II.Part

Accretion of matter onto SgrA*
Radio, X-ray variability
NIR/X-ray correlations
Adiabatic expansion
NIR polarization
Disk and jet models
Alternative models for SgrA*
Intermediate Mass BHs
MBHs in external galaxies

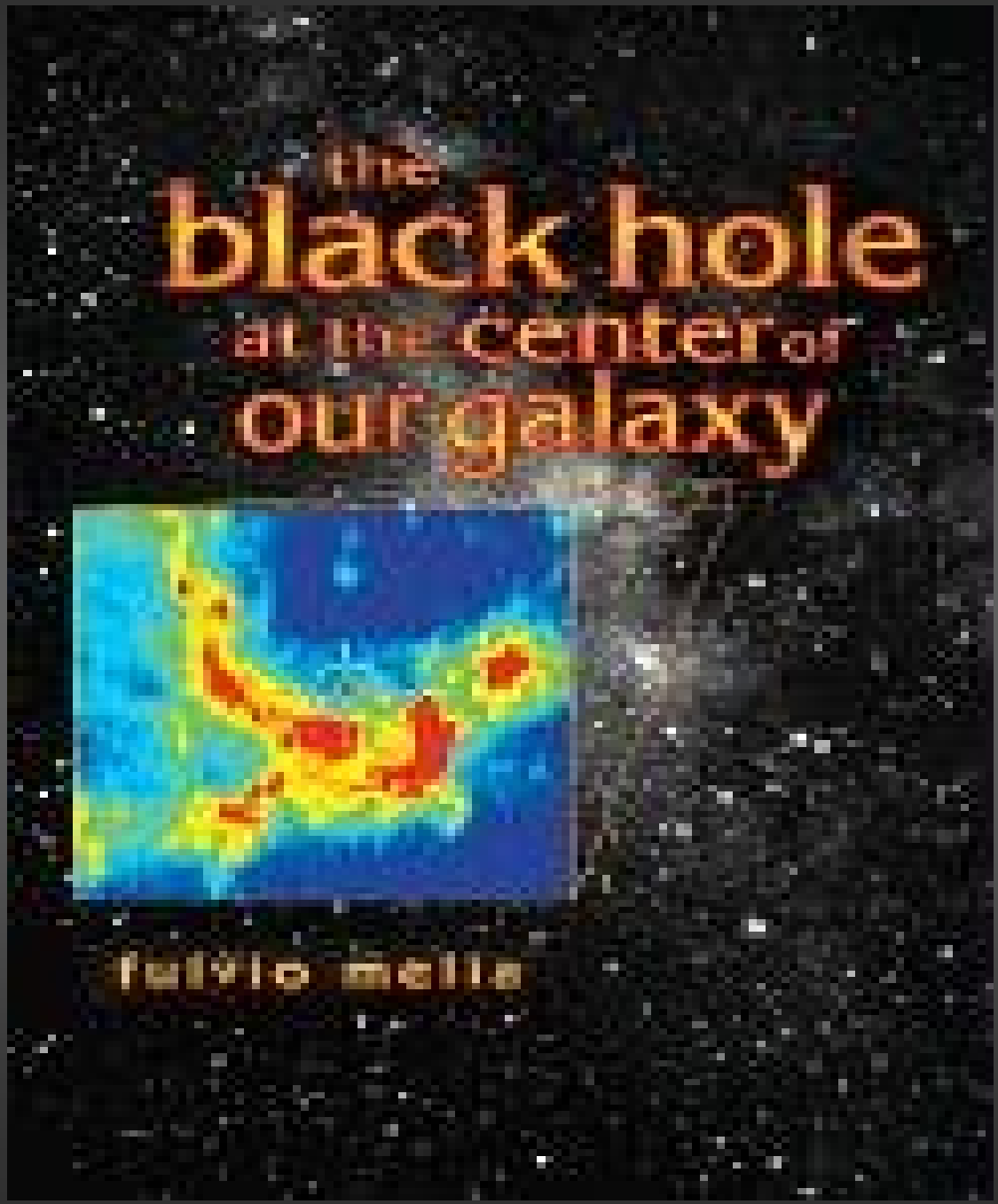
Future Experiments

Book on the Galactic Center



Eckart, Schödel, Straubmeier 2005; Imperial College Press; ISBN 1-86094-567-8

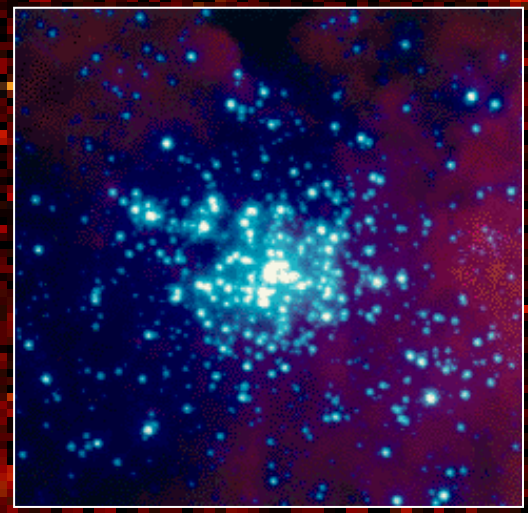
Book on the Galactic Center



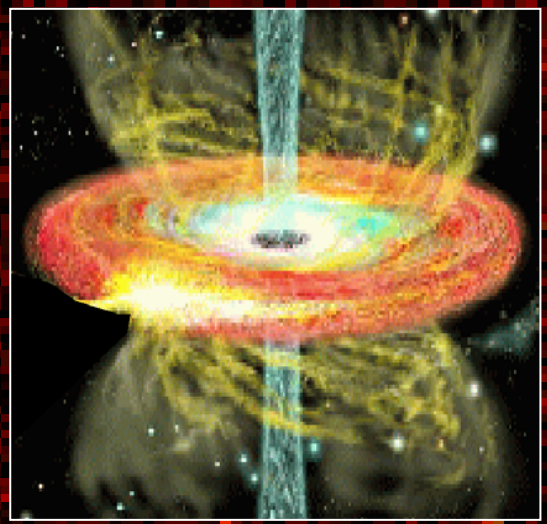
Melia 2004;
Princeton Universiy Press 2003,
ISBN 069 109 5051

Active Galactic Nuclei: Stars or Black Holes?

How can one explain the large energy release of Active Galactic Nuclei?



$E < 0.005\ Mc^2$



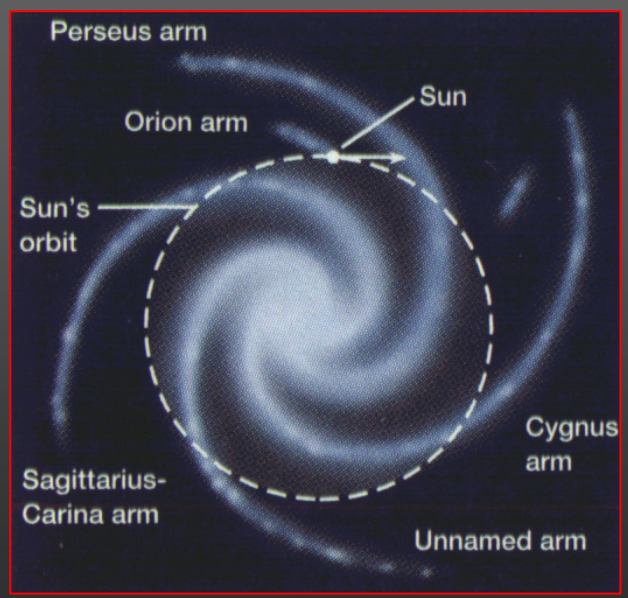
mass distribution

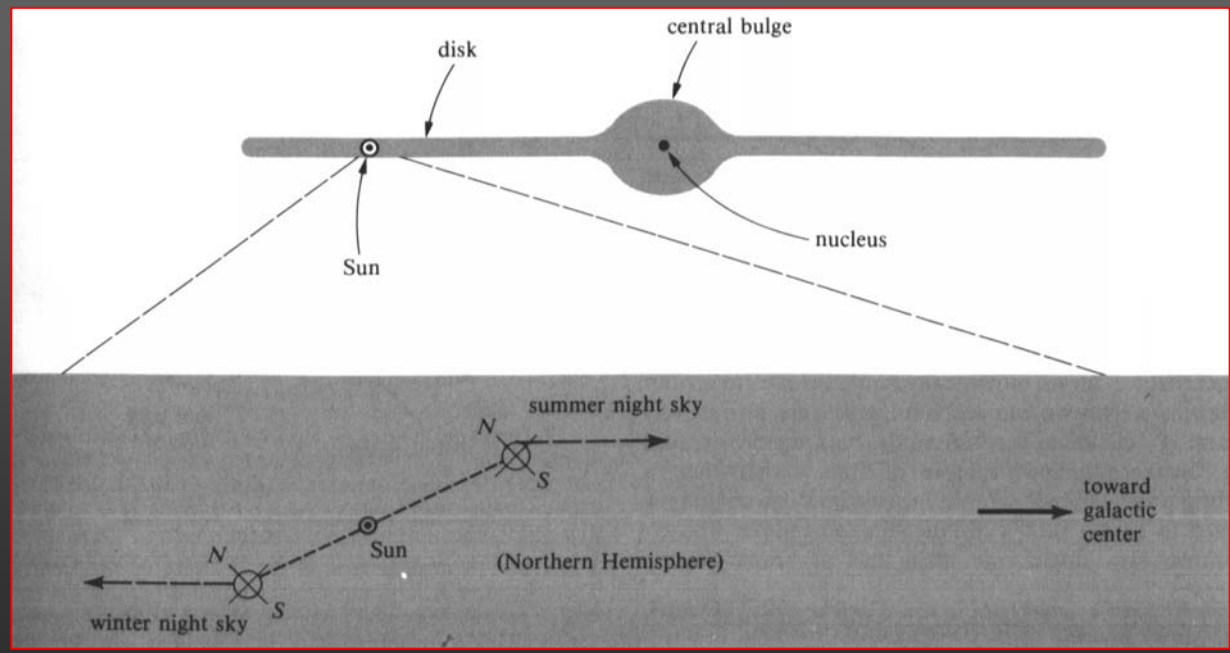
$E < 0.1\ Mc^2$
variable X-ray and γ-ray emission
relativistische radio jets

HST WFPC 2

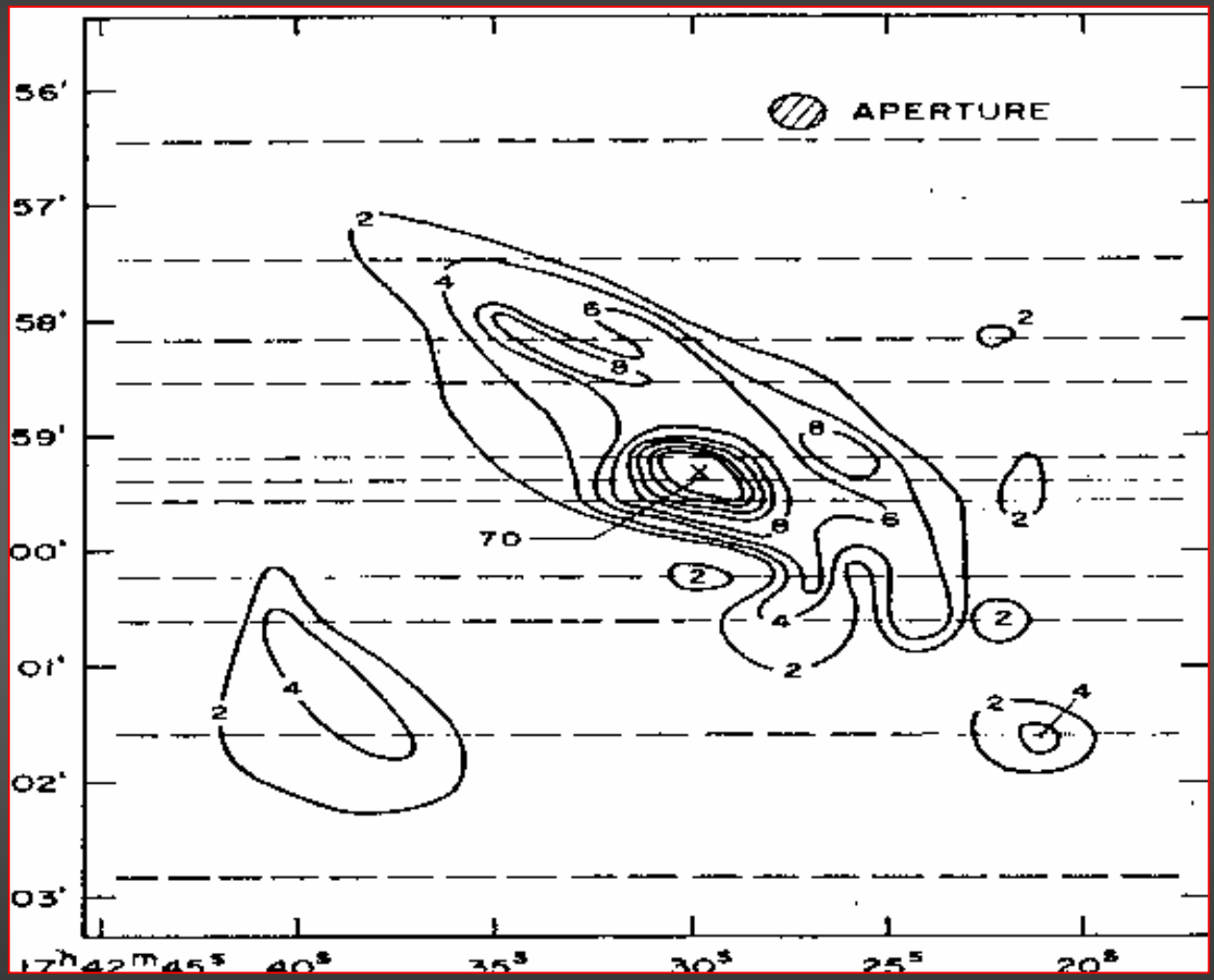
Towards the Center of the Milky Way

closest galactic nucleus
8 kpc distance
Av=30 Ak=3
NIR observations required!



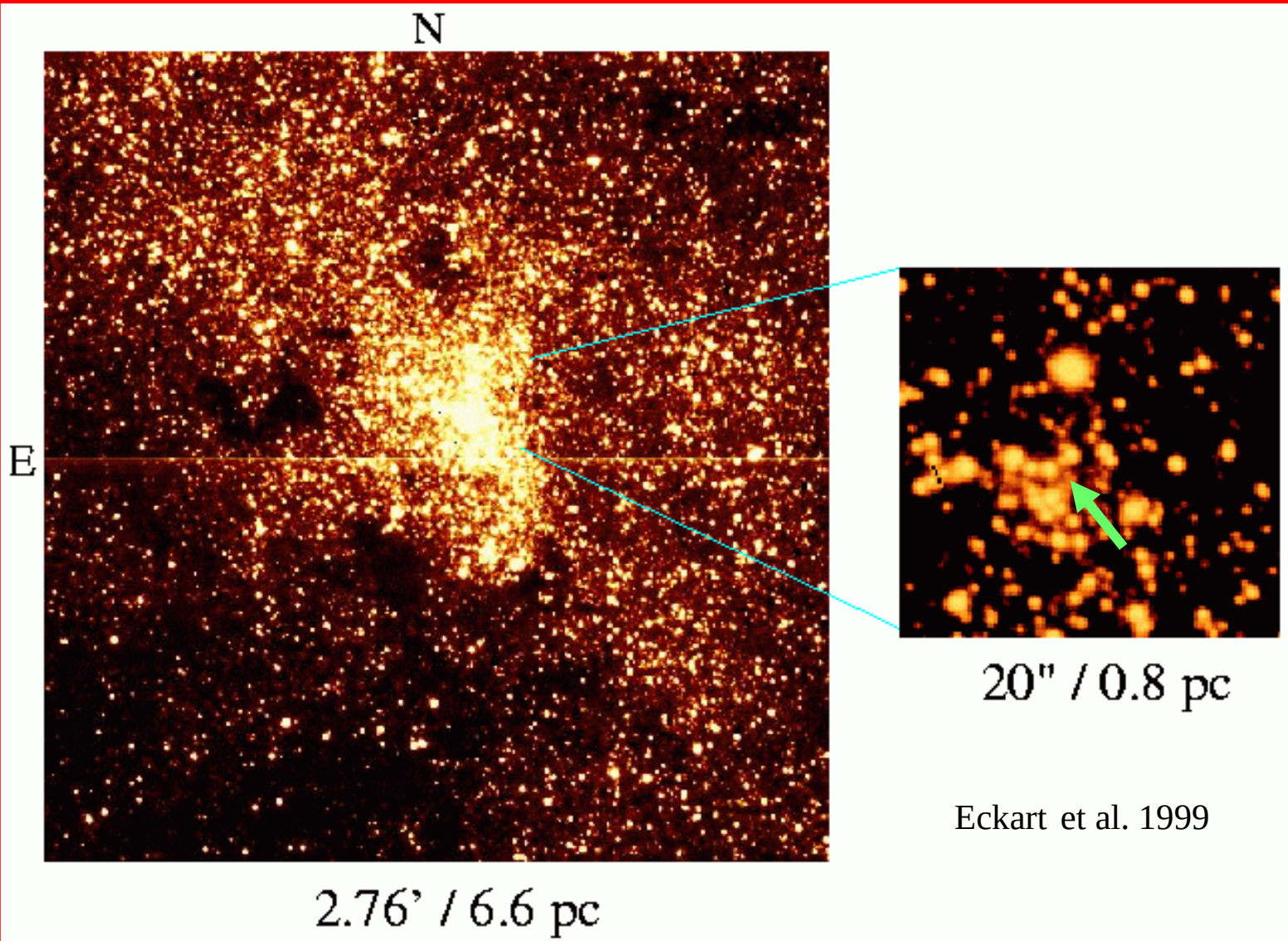


First 2.2μm scans through the GC



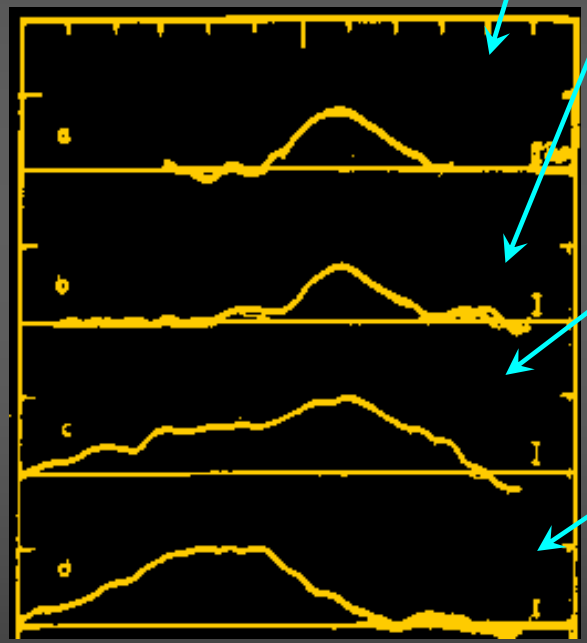
R.A. single detector strip-chart scans (Becklin & Naugebauer 1968)

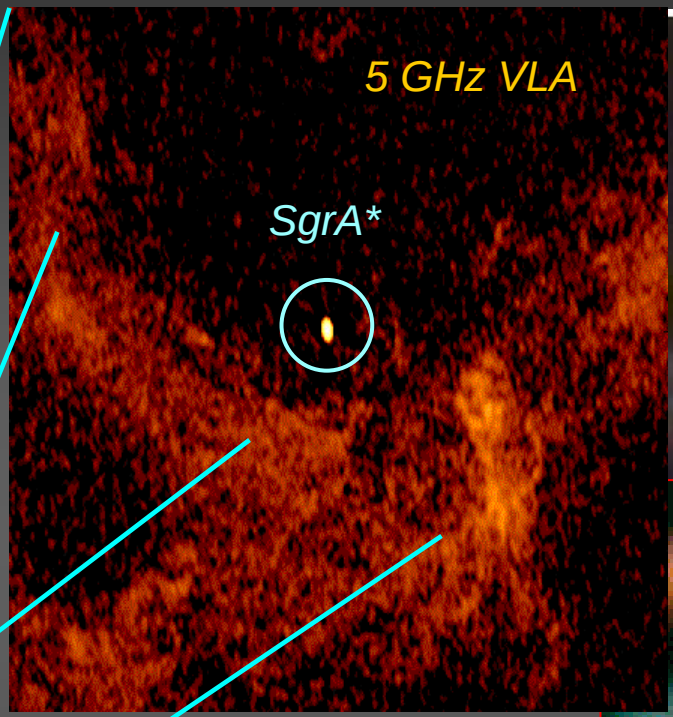
K-band exposure with ISAAC with VLT/UT1

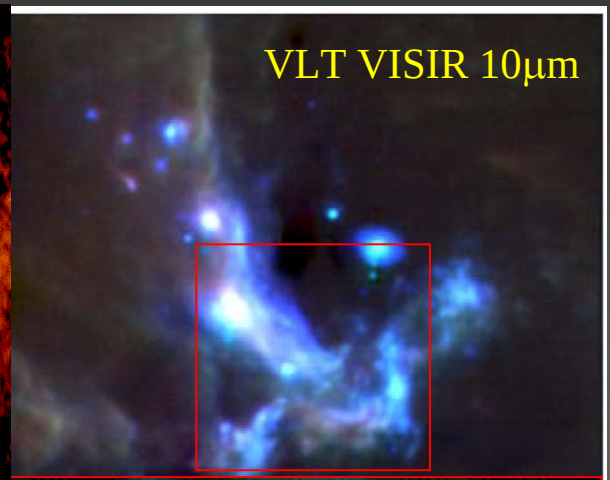


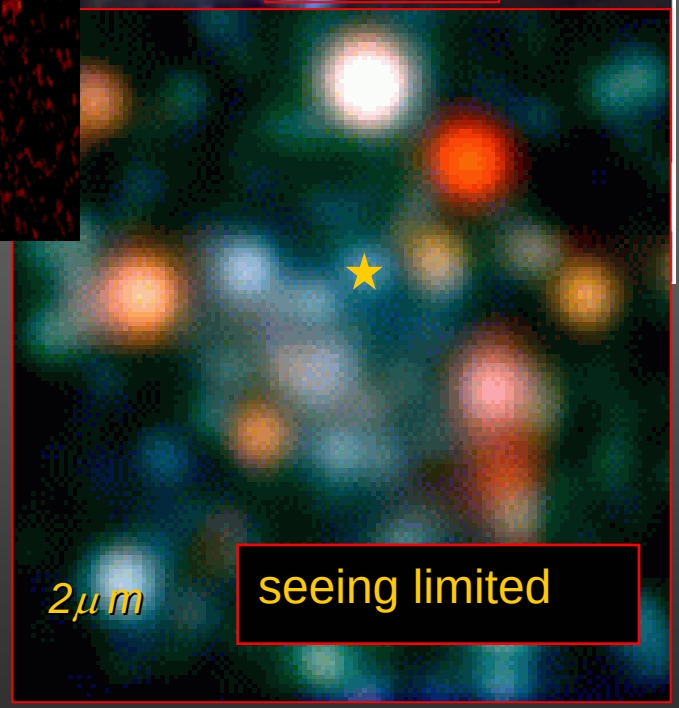
Eckart et al. 1999

The Galactic Center





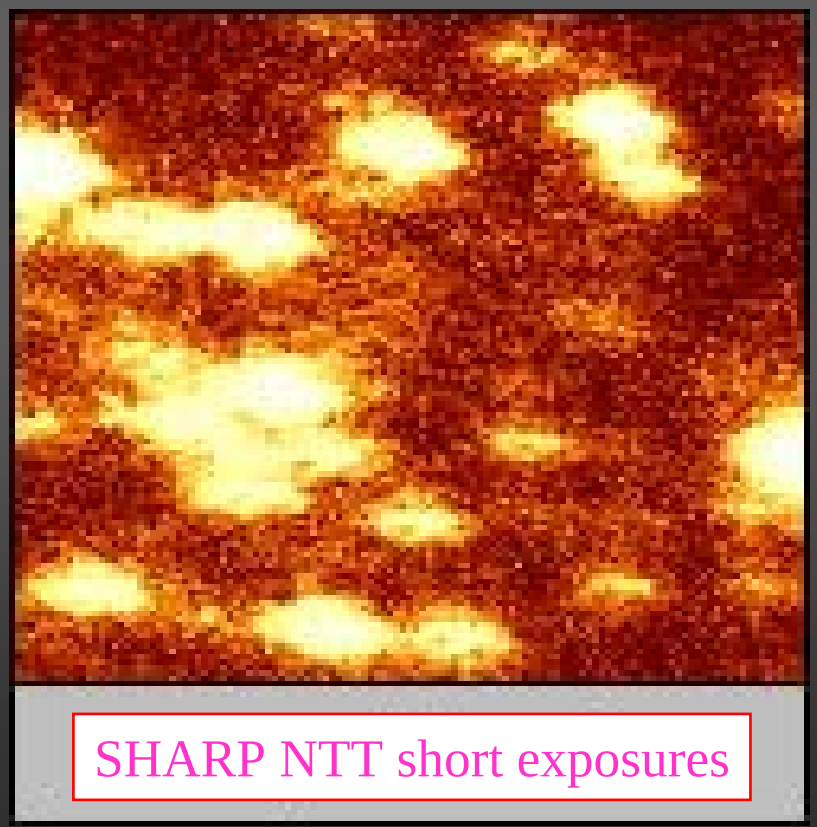




Wollman et al. 1977, Lacy et al. 1979, 1980, Lo et al. 1983, DePoy and Sharp 1991

Speckle Interferometry

Via short exposures (typically 100 ms) the influence of the atmosphere on the image can be recorded and corrected for.



SHARP NTT short exposures

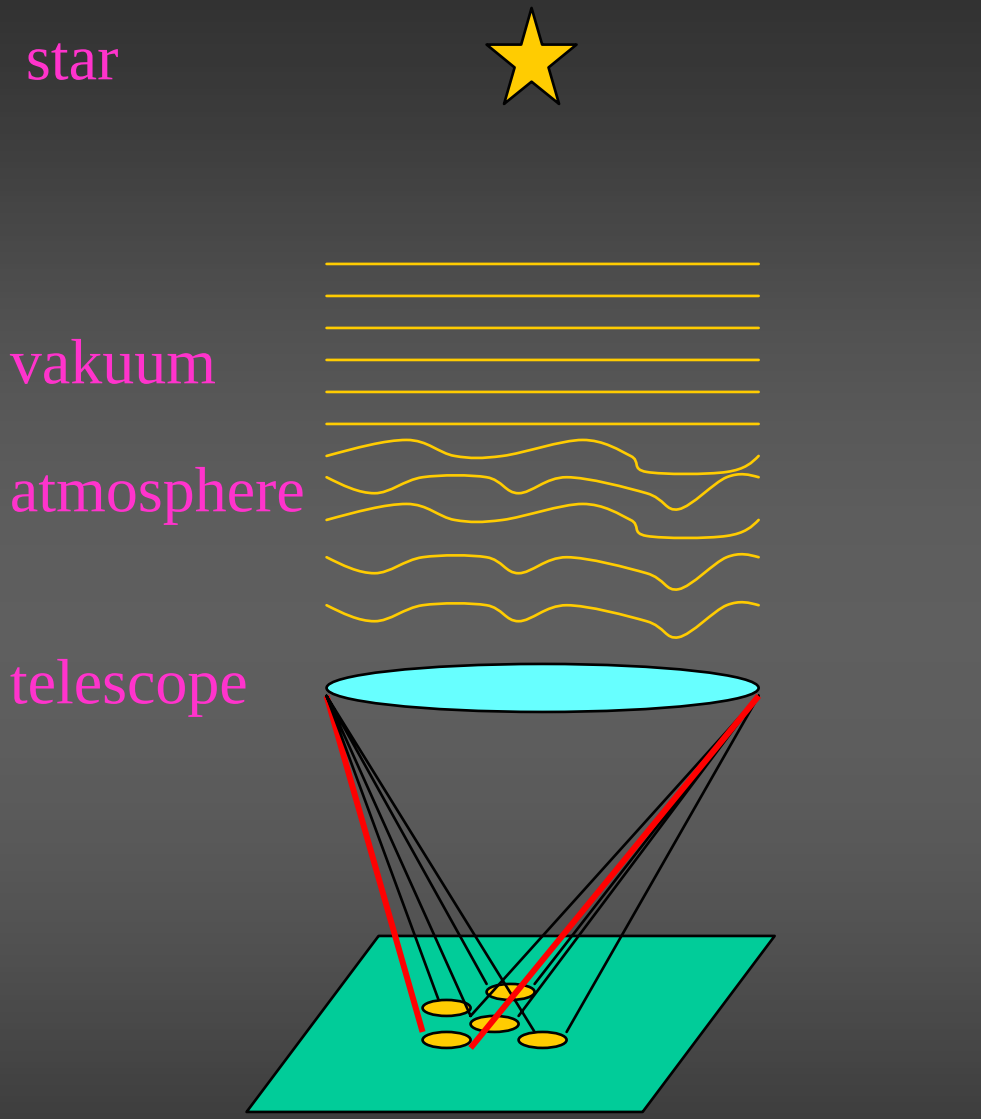
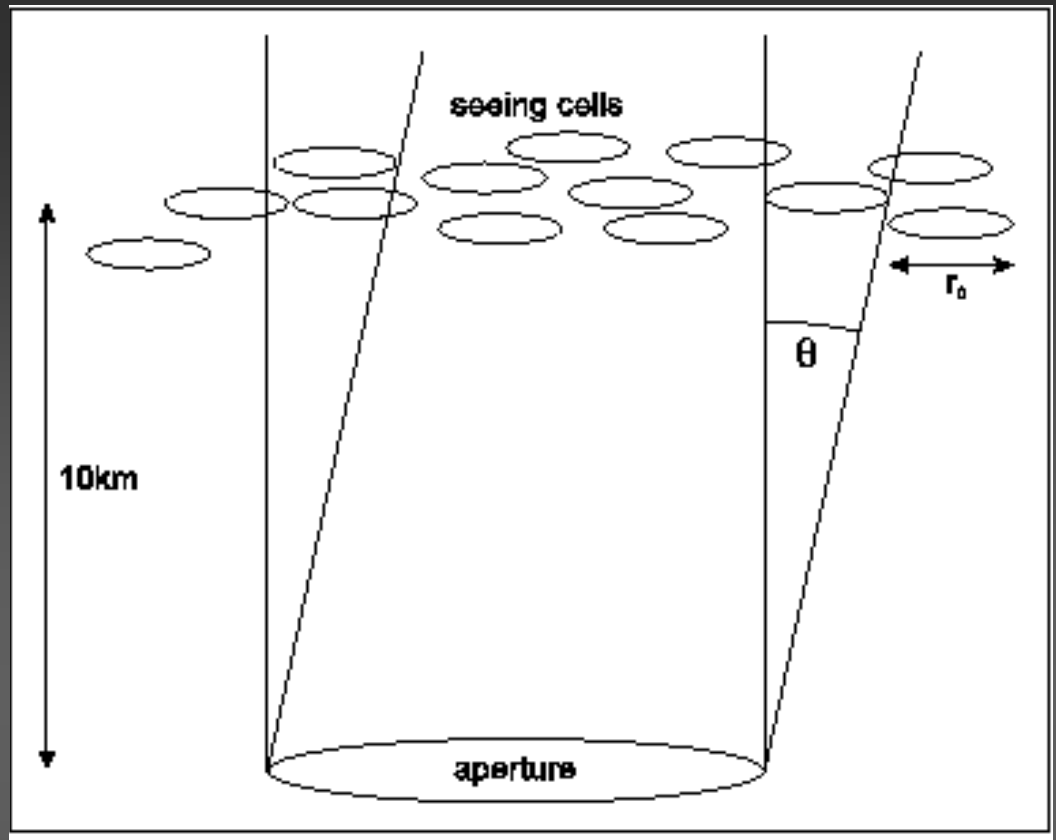
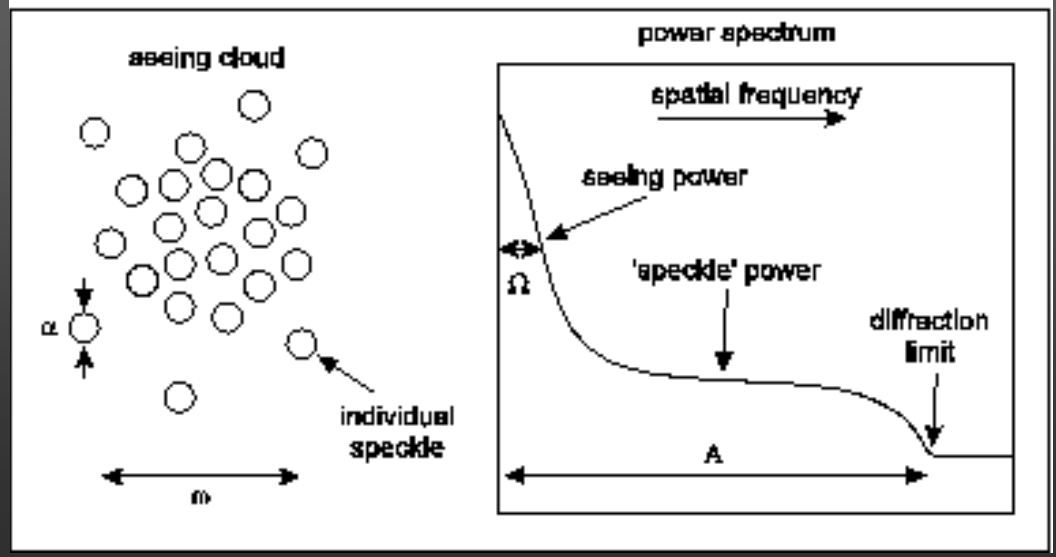


Image Formation



The apparent diameter of a seeing cell determines the size of the isoplanatic patch



Speckles can be regarded as distorted images of the object at the telescope's diffraction limit

Image Formation

image plane

$$I(x,y) = O(x,y) * P(x,y)$$

image is object convolved with PSF

Fourier plane

$$i(u,v) = o(u,v)\,p(u,v)$$

$$|\langle i(u,v)\rangle|^2 = o^2(u,v)\,|\langle T(u,v)\rangle|^2$$

long exposure power spectrum

$$|\langle i\rangle|^2 = |\langle a e^{i\phi}\rangle|^2$$

$$\langle |\, i(u,v)\,|^2 \rangle = o^2(u,v)\langle |\, T(u,v)\,|^2 \rangle$$

short exposure power spectrum

$$\langle |\, i\,|^2 \rangle = \langle i^* \times i \rangle = \langle a^2 \rangle \langle e^{-i\phi} e^{i\phi} \rangle = \langle a^2 \rangle$$

information at high spatial frequencies is preserved!

Seeing

$$\langle T(u,v)\rangle = T_S(u,v)T^*(u,v)$$

Telescope tranfer function:T*
(autocorrelation of aperture)

$$w^2 = u^2 + v^2$$

Seeing transfer function: Ts

$$T_S(\omega) \approx \exp(-3.44\frac{\lambda|w|^{5/3}}{r_0})$$

assuming a Kolmogorov power law for the atmospheric turbulence

$$r_0 \propto \lambda^{6/5} \times (\cos(\gamma))^{3/5}$$

r_0 Fried size of turbulent cells
γ zenith angle

$$\omega \approx \lambda / r_0$$

angular diameter of a (Fried) seeing cell

$$\omega \propto \lambda^{-1/5}$$

The seeing is better in the Infrared wavelength domain!!

Also: γ should be small!
Go to Chile!!

Shift-and-Add Algorithm

$$I(x,y) = O(x,y) * P(x,y) + N(x,y)$$

$$S(x,y) = \frac{1}{M}\sum_{m=1}^{M} I_m(x + x_m, y + y_m)$$

I : image ; O : object

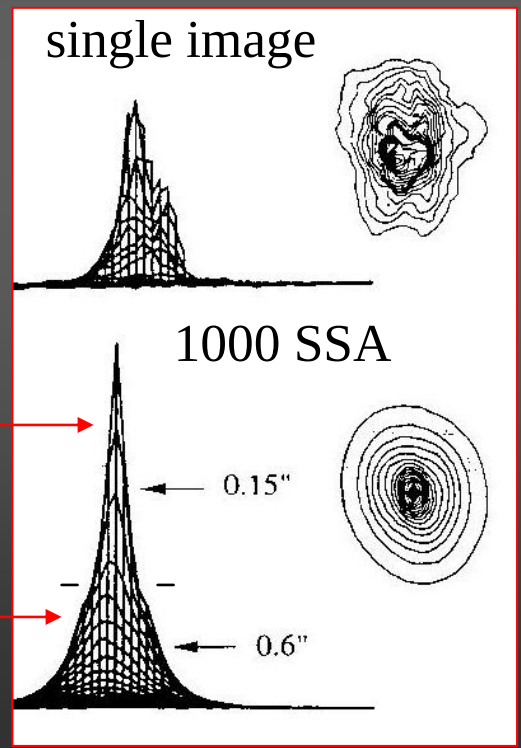
P : PSF ; N : noise

$$S(x,y) = \frac{1}{M}\left(O(x,y) * \sum_{m=1}^{M} P_m(x + x_m, y + y_m) + \sum_{m+1}^{M} N_m(x + x_m, y + y_m) \right)$$

$$S(x,y) = \frac{1}{M}\left(O(x,y) * P_s(x,y) + N_s(x,y)\right)$$

diffraction limited part $R \propto \lambda / D$

seeing limited part $R \propto \lambda / r_0$



Lucy Deconvolution

$\Psi_1 = I$

$\Phi_i = \Psi_i \otimes P$

$R = \left(I / \Phi_i\right) * P$

$\Psi_{i+1} = \Psi_i \times R$

deconvolved image

diffraction limited part $R \propto \lambda / D$

seeing limited part $R \propto \lambda / r_0$

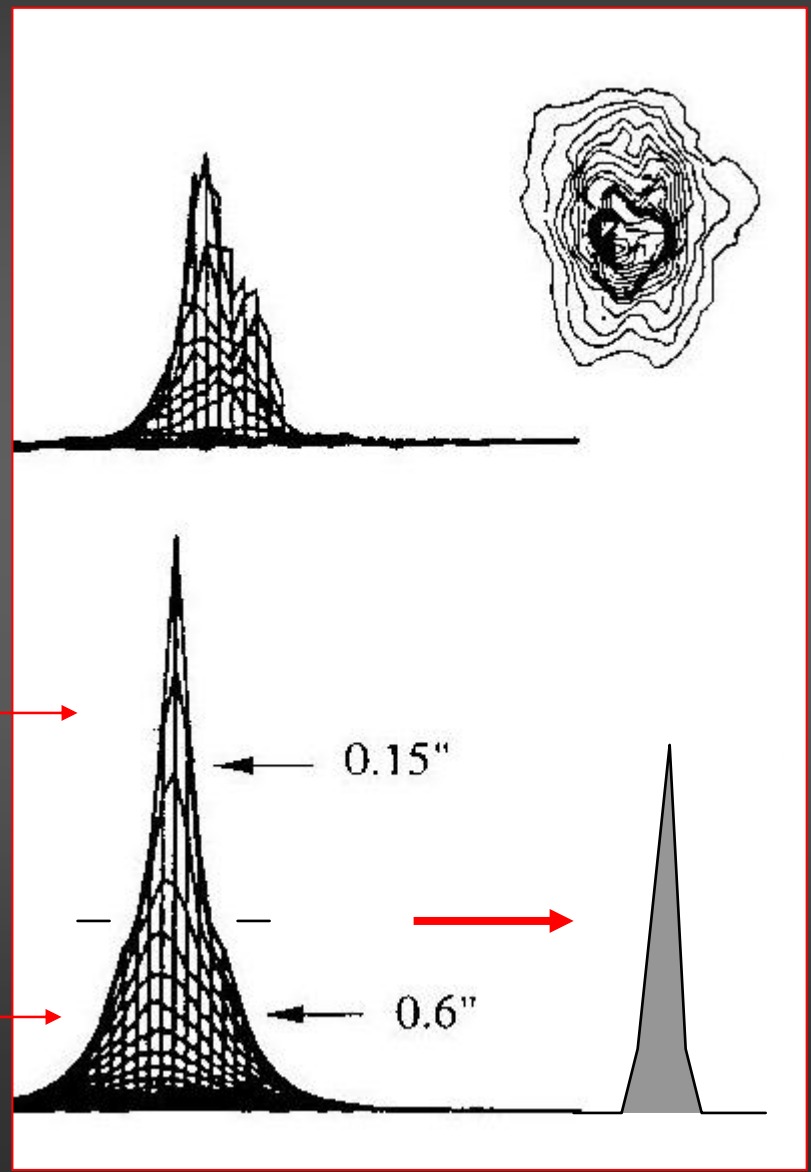
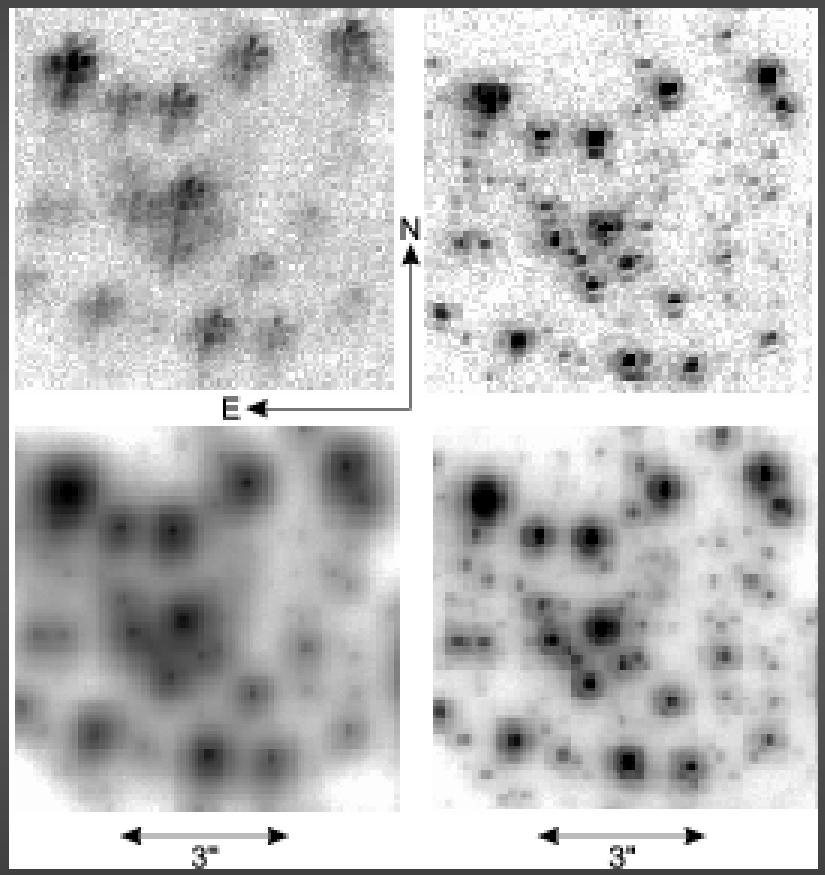
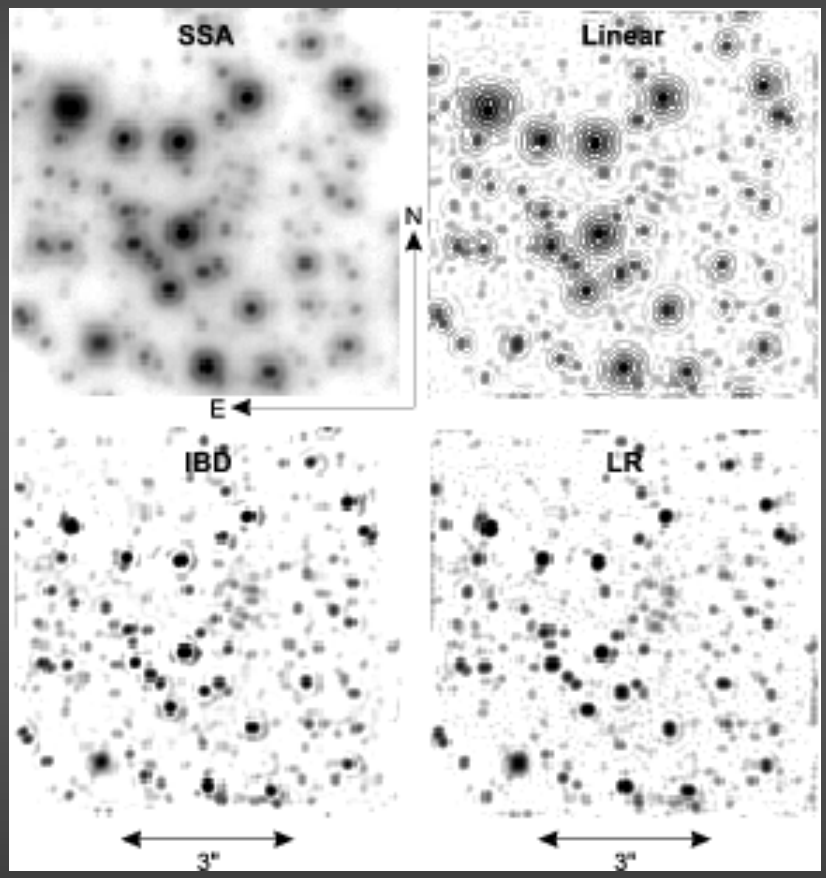


Image Reconstruction



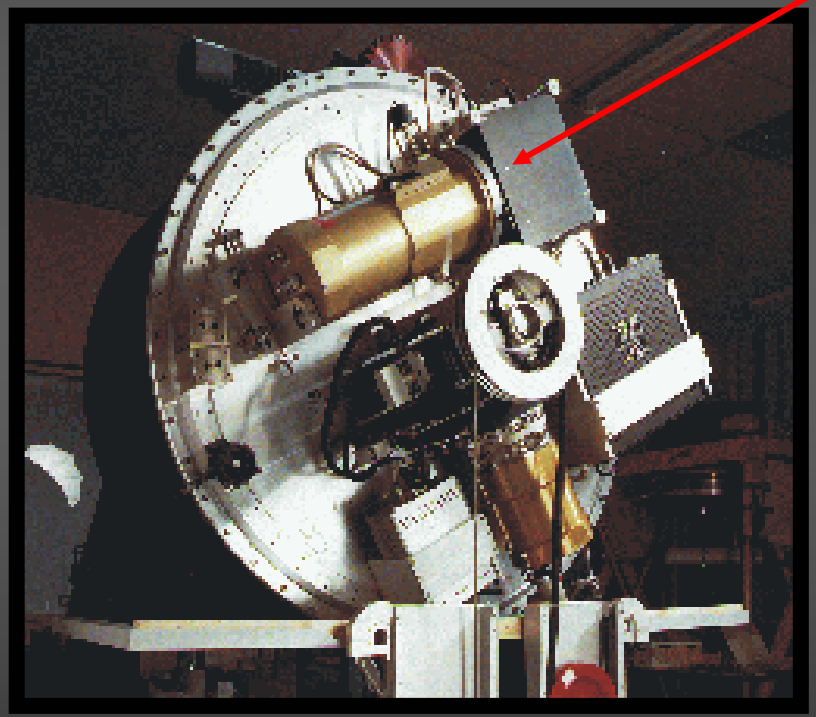
average and excellent speckle image;
average (15% Strehl) and best (30% Strehl)
SSA result of 100 images



Deconvolution methods: SSA, Linear,
Blind deconvolution, Lucy-Richardson

NTT Speckle Interferometry and Adaptive Optics at the VLT UT4

Proper motions: SHARP I + NAOS/CONICA



ESO NTT La Silla since 1992

ESO VLT UT4 Paranal since 2002

Keck since ~1995

proper motions from imaging

Proper motions

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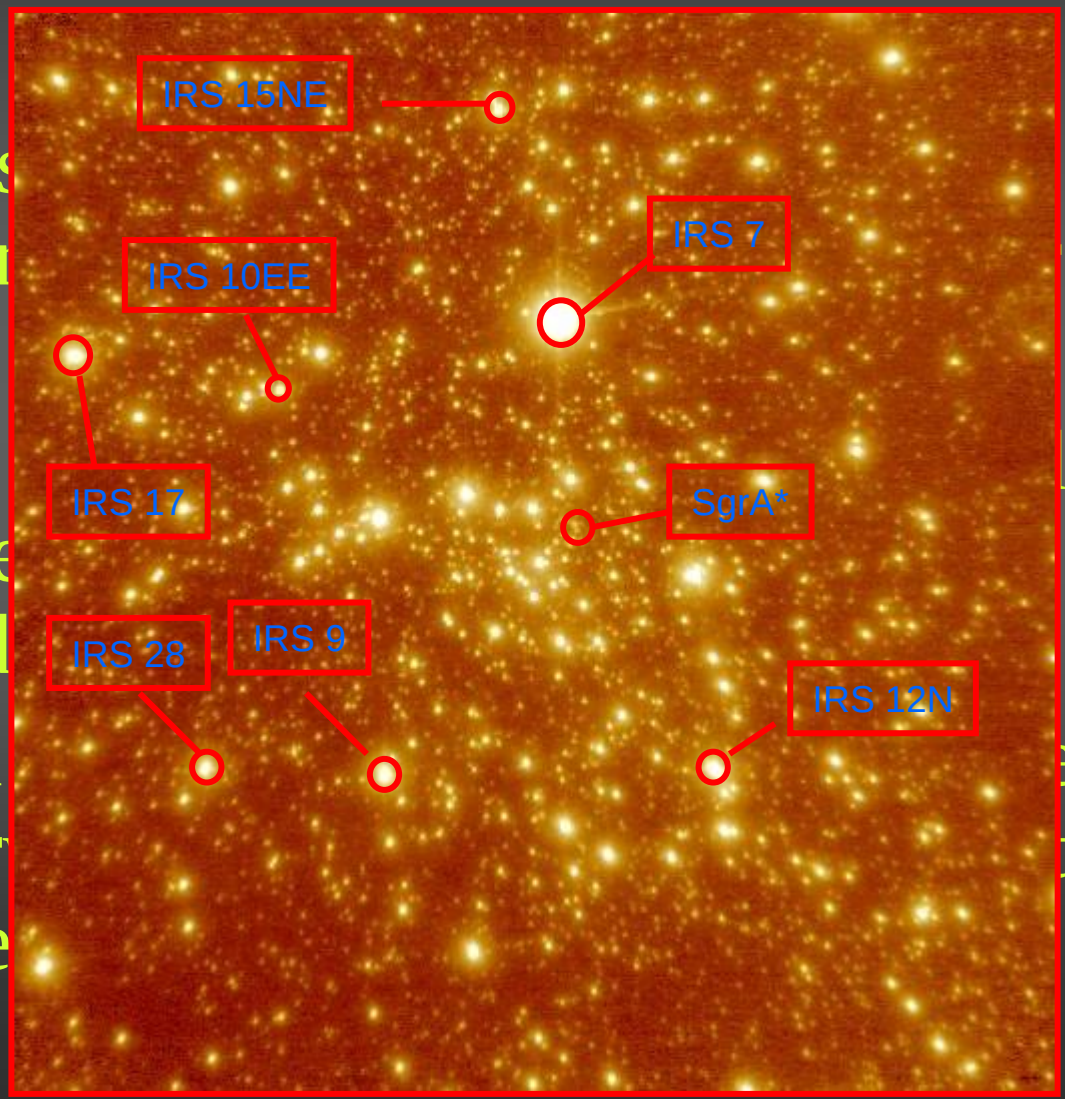
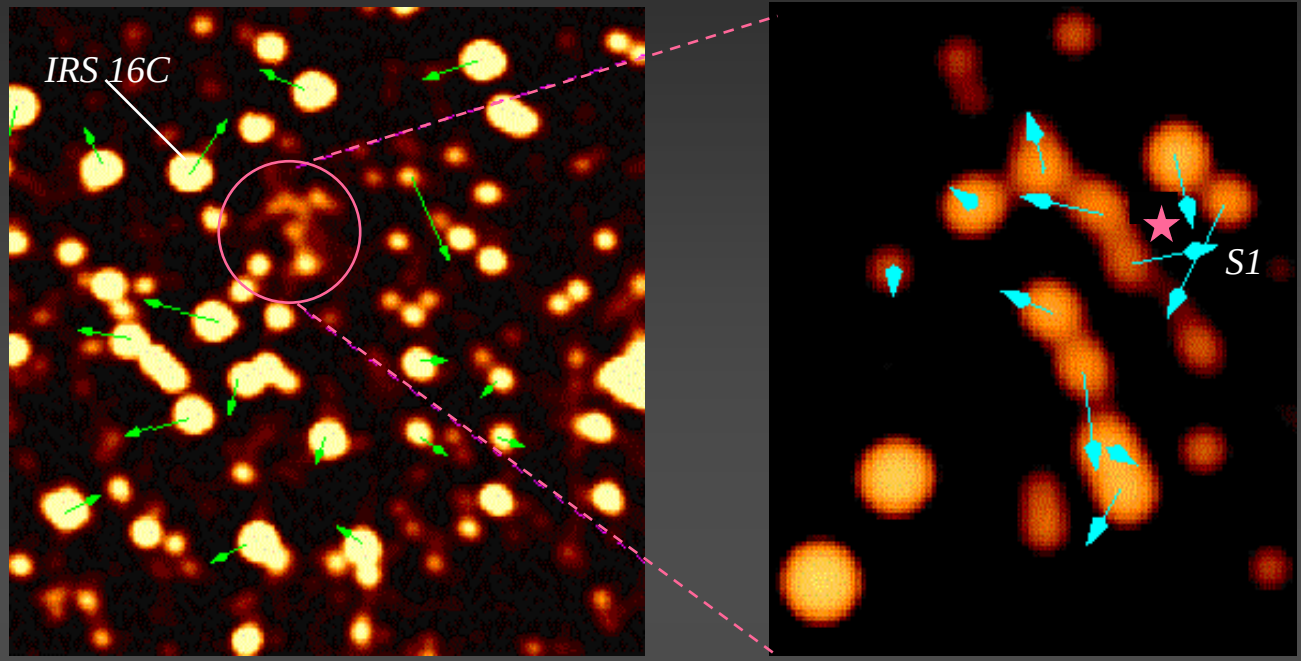
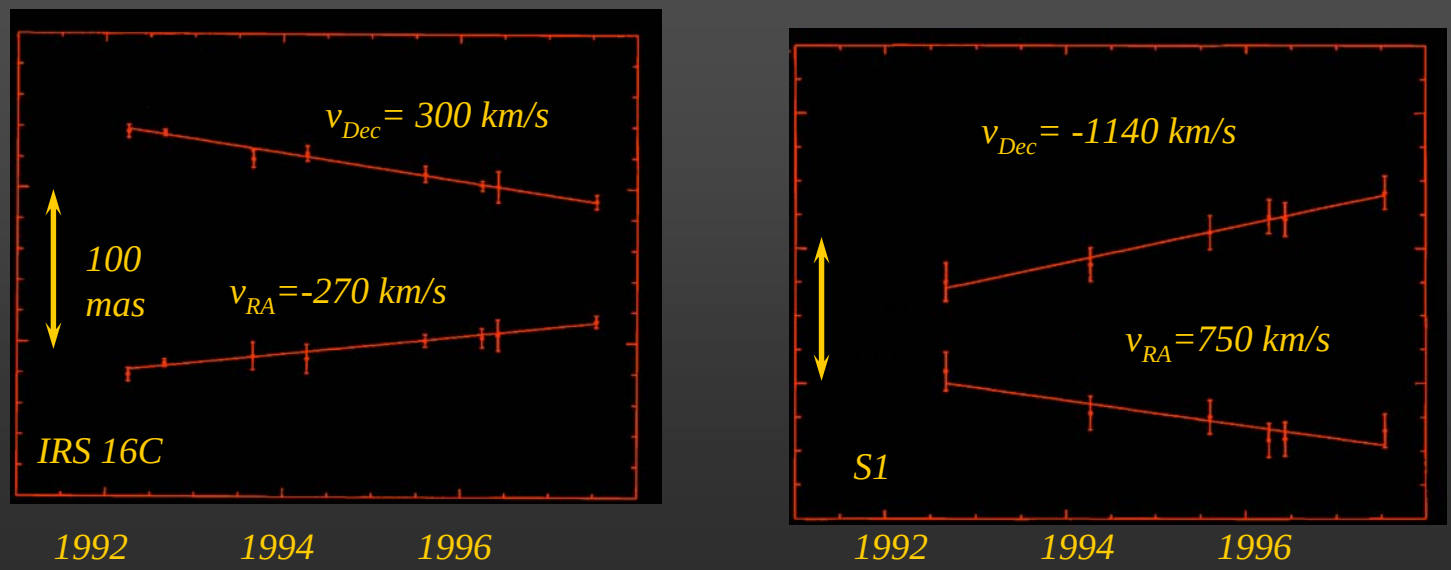


Radio/NIR Restframe:
Reid et al. 2003
Menten et al. 1998

Stellar Proper Motions



Eckart und Genzel 96,97, Genzel et al. 1997



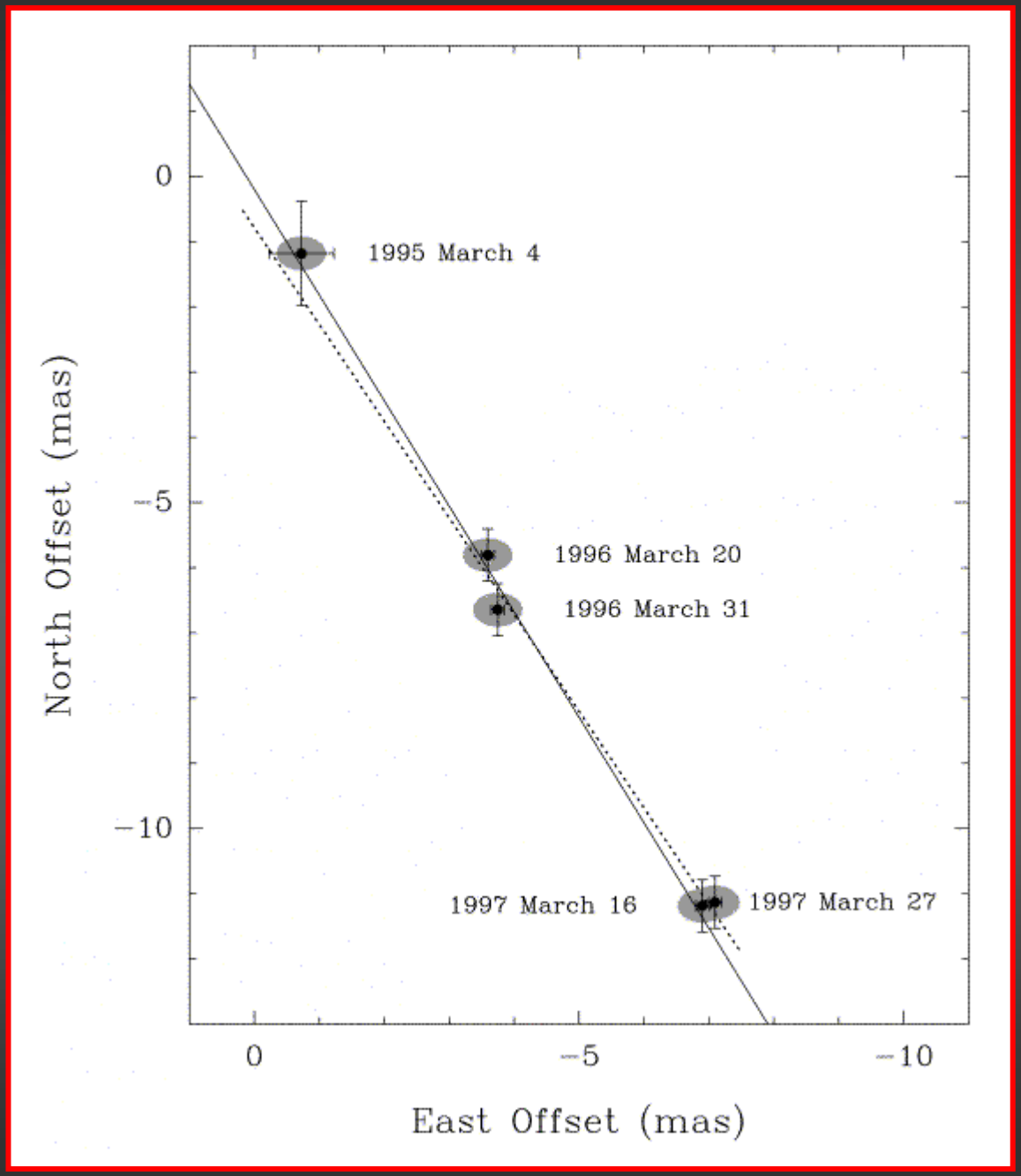
The Galactic Center

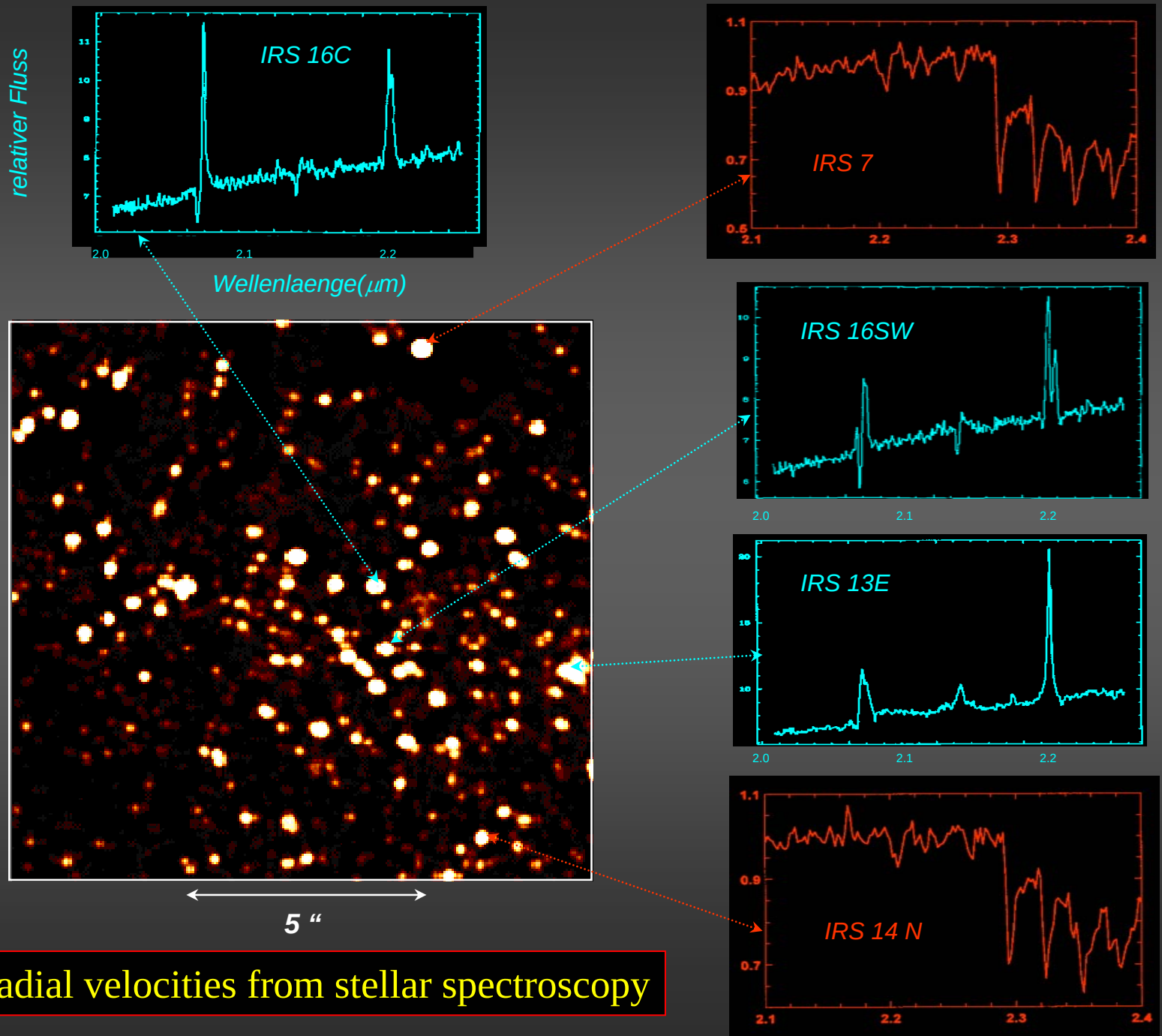
VLBA measurements of the SgrA* proper motion give 5.9 mas/yr almost entirely in the Galactic plane consistent with the suns motion of 219 km/s at 8 kpc.

The upper limit on the intrinsic proper motion of 20 km/s indicates a lower limit to the SgrA* mass of 1000 M_{sun}

Reid et al. 1999 ApJ 524, 816

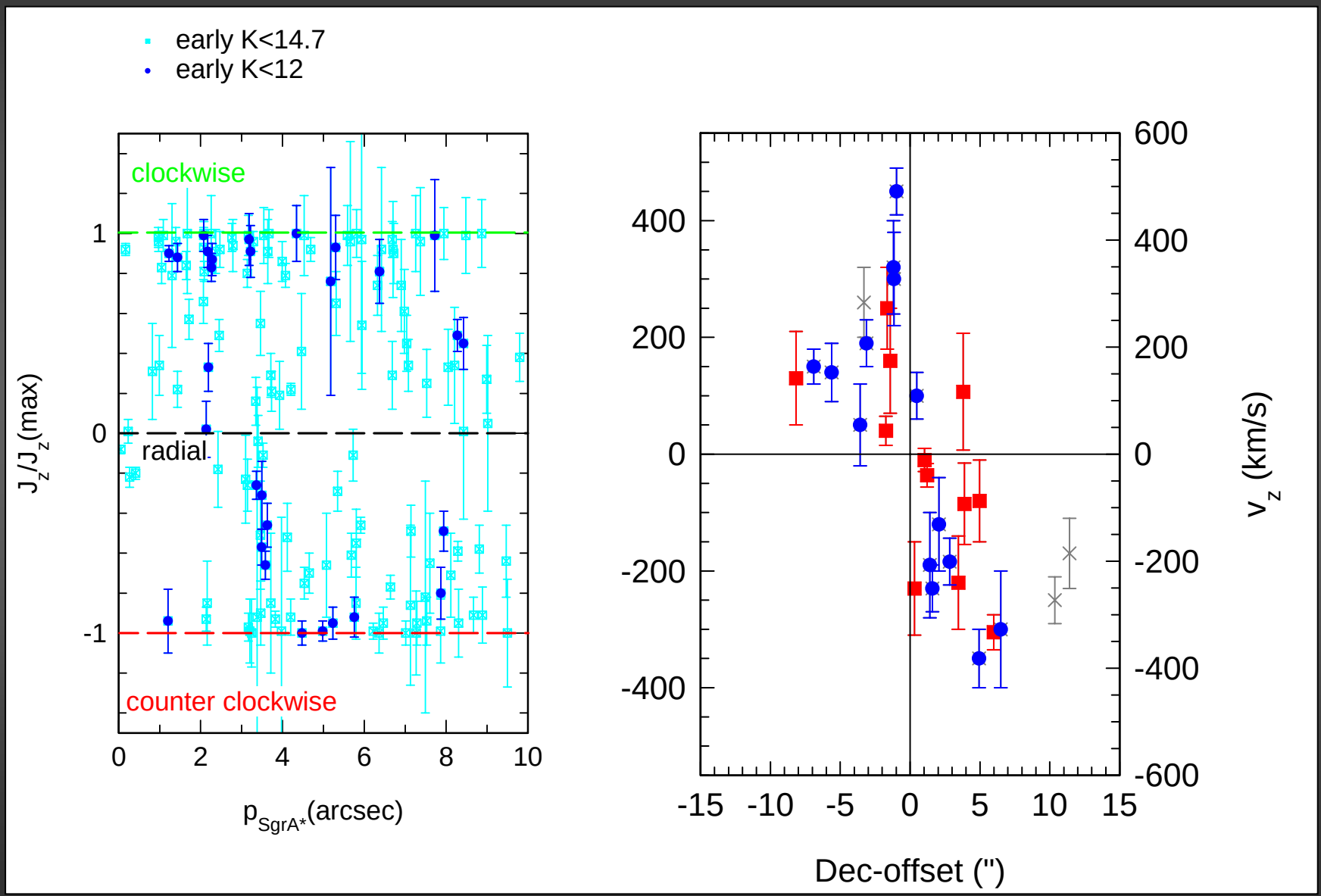
Backer et al. 1996





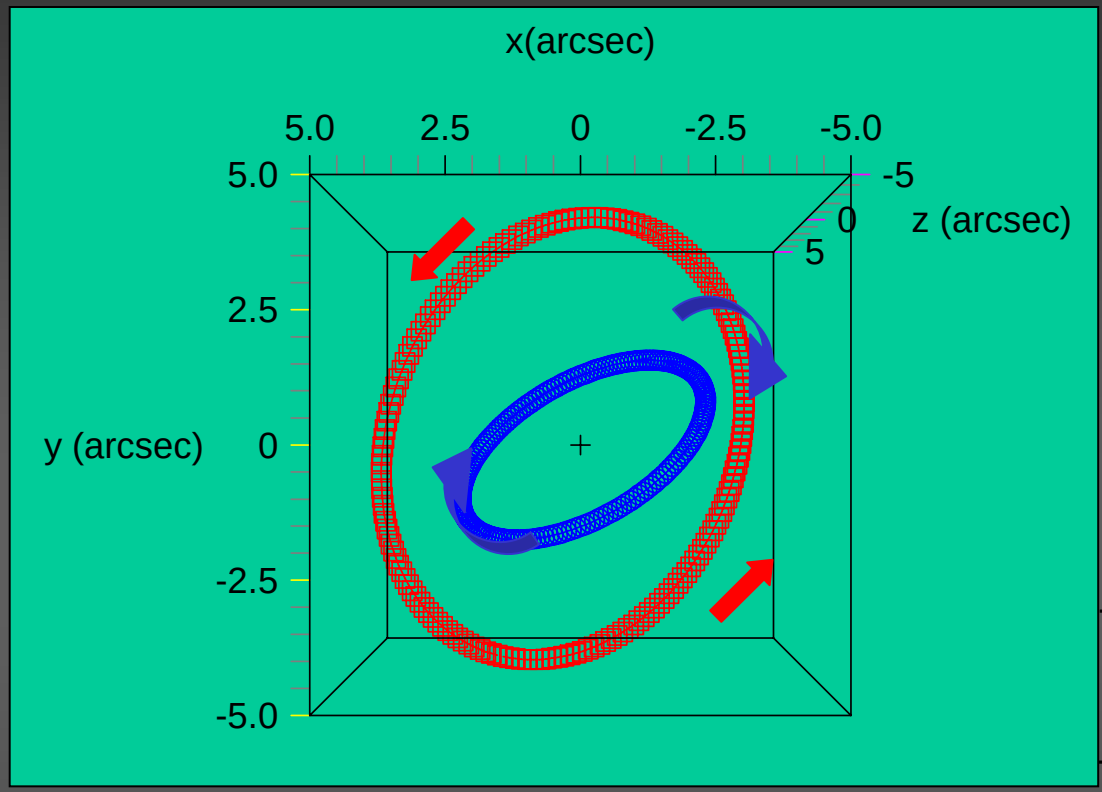
radial velocities from stellar spectroscopy

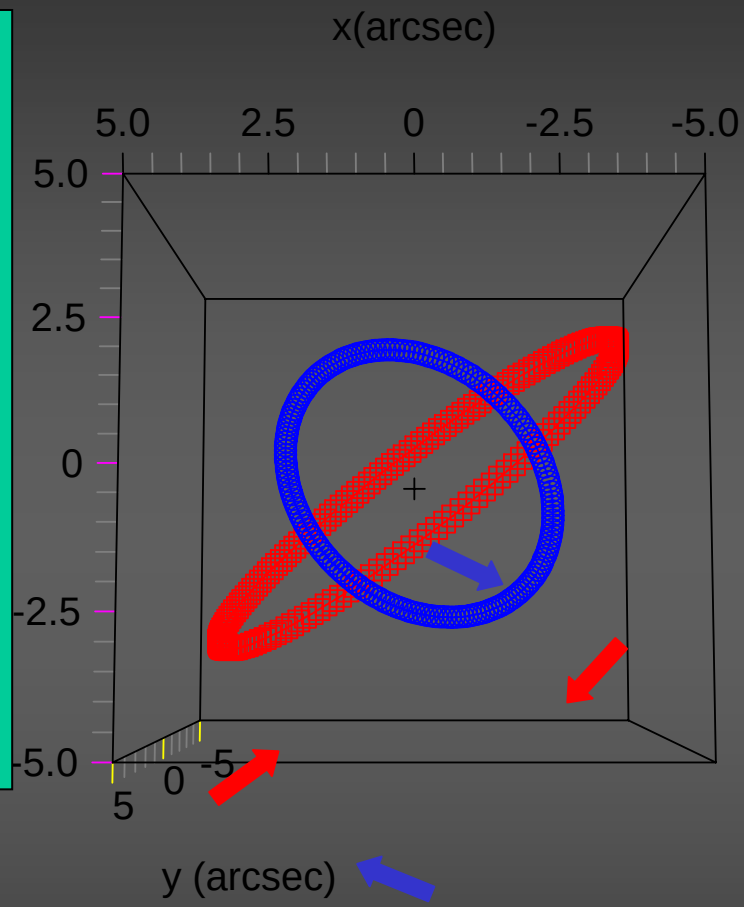
Overall rotation of early type stars



Genzel et al. 2003, Ap.J. (astro-ph 0305423), Ott et al. 2004 (1000 proper motions, 200 3Dvels)

Rotating disks of early type stars





SPIFFI spectroscopy:
The two disks have *very similar short-lived stellar populations* (LBV, Wolf-Rayet…)

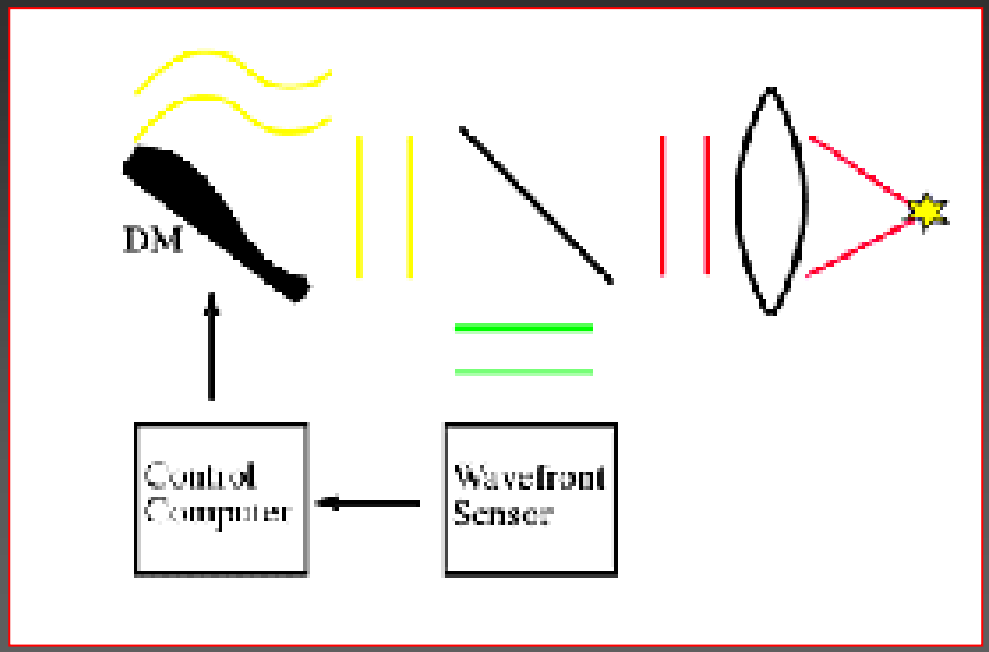
➔ ***Coeval formation***

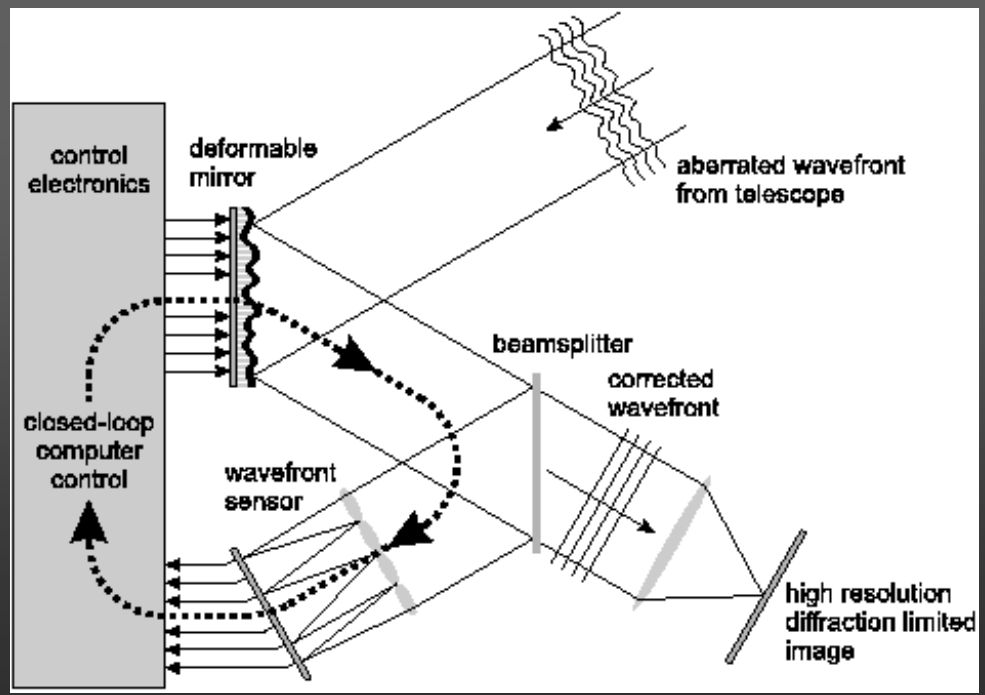
Genzel et al. 2003, Ap.J. 2003 (astro-ph 0305423)
Levin & Beloborodov, Ap.J. 2003

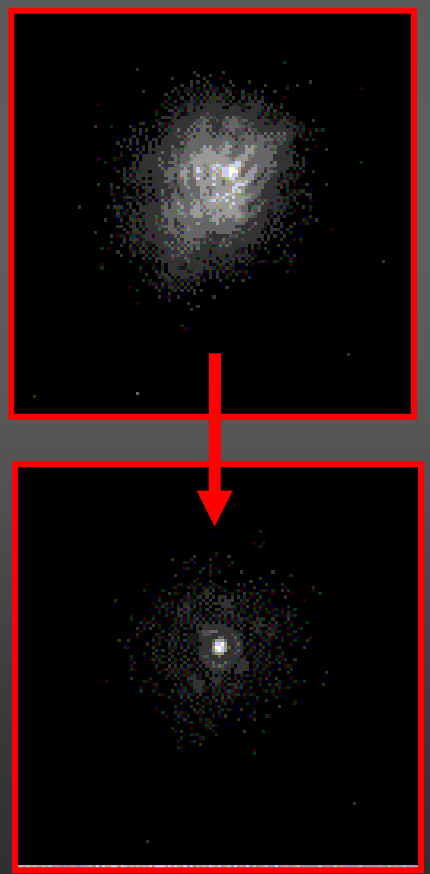
Towards the central arcsecond

Adaptive Optics

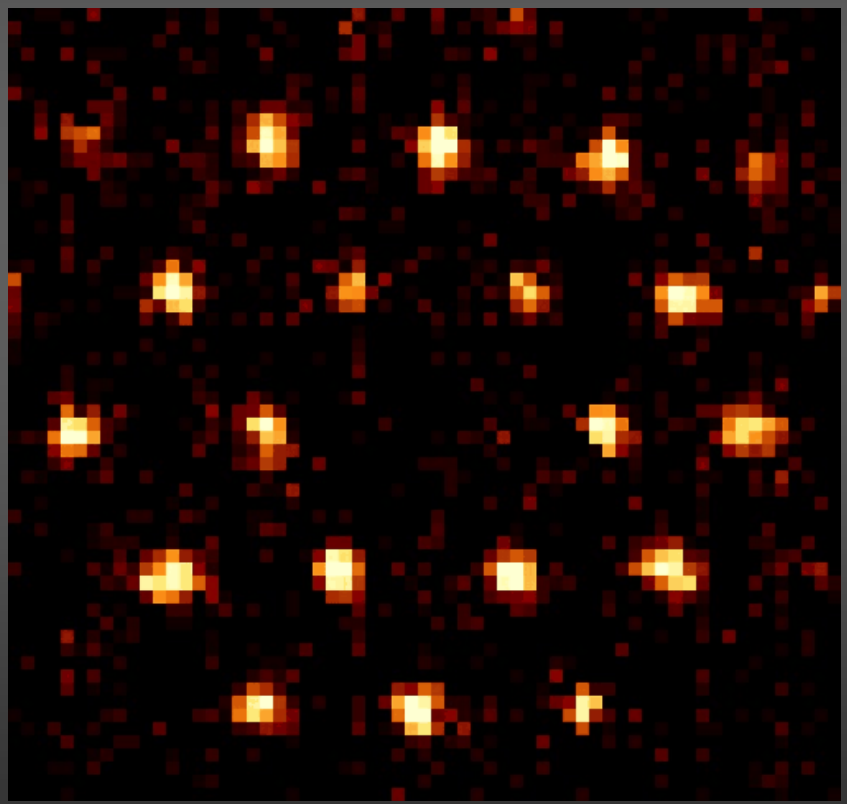
distorted wavefront is measured online and straightened via a deformable mirror

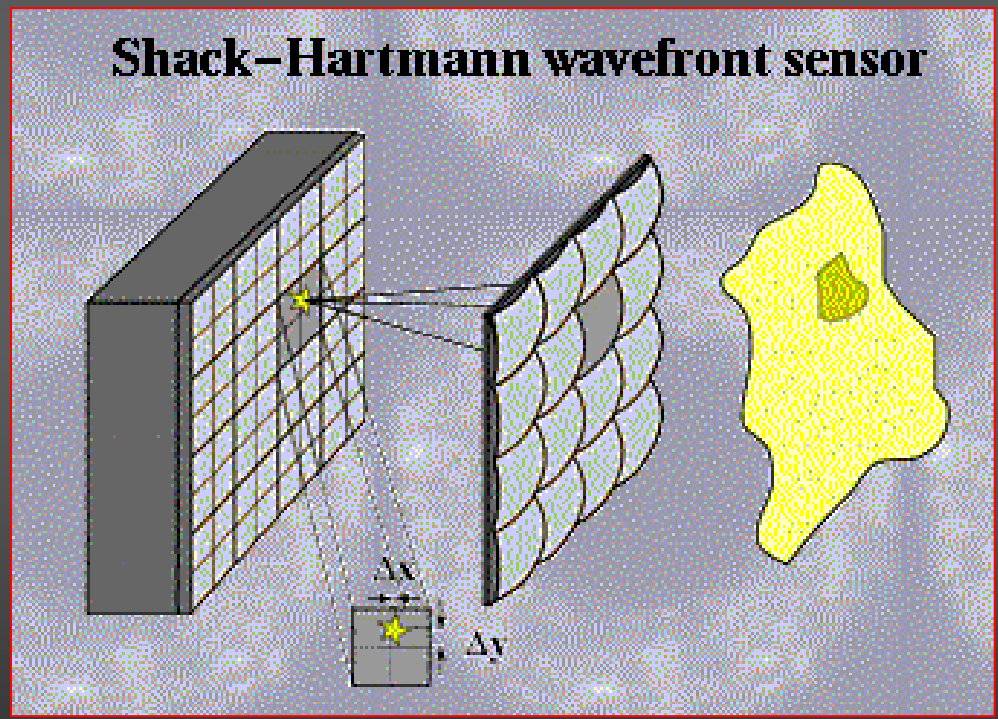






Adaptive Optics





Adaptive Optics

Across the apperture the wavefront sensor delivers m=1….M/2 positions and M measured gradients of the wavefromt ϕ represented via k=1….K Zernicke polynomials as orthogonal wavefront modes:

$$\phi = \sum_{k=1}^{K} a_k Z_k(x,y)$$

Gradients are then defined via:

$$\frac{\partial \phi}{\partial x}\Big|_m = \sum_{k=1}^{K} a_k \frac{\partial Z_k(x,y)}{\partial x}\Big|_m$$

$$\frac{\partial \phi}{\partial y}\Big|_m = \sum_{k=1}^{K} a_k \frac{\partial Z_k(x,y)}{\partial y}\Big|_m$$

s are the gradients
a are the modal coefficients
B is the corresponding matrix

$$s = [B]a$$

Adaptive Optics

In detail the quanities in are given by:

$$s = [B]a$$

$$s = \begin{pmatrix} \frac{\partial \phi}{\partial x}\Big|_1 \\ \cdots\cdots \\ \frac{\partial \phi}{\partial x}\Big|_{\frac{M}{2}} \\ \frac{\partial \phi}{\partial y}\Big|_1 \\ \cdots\cdots \\ \frac{\partial \phi}{\partial y}\Big|_{\frac{M}{2}} \end{pmatrix} \qquad a = \begin{pmatrix} a\big|_1 \\ \cdots\cdots \\ a\big|_{\frac{M}{2}} \\ a\big|_1 \\ \cdots\cdots \\ a\big|_{\frac{M}{2}} \end{pmatrix}$$

$$[B] = \begin{pmatrix} \mu_{1,1} & \mu_{2,1} & \cdots\cdots & \mu_{K,1} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ \mu_{1,\frac{M}{2}} & \mu_{2,\frac{M}{2}} & \cdots\cdots & \mu_{K,\frac{M}{2}} \\ \xi_{1,1} & \xi_{2,1} & \cdots\cdots & \xi_{K,1} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ \xi_{1,\frac{M}{2}} & \xi_{2,\frac{M}{2}} & \cdots\cdots & \xi_{K,\frac{M}{2}} \end{pmatrix}$$

with matrix elements:

$$\mu_{k,m} = \frac{\partial Z_k(x,y)}{\partial x}\Big|_m \qquad \xi_{k,m} = \frac{\partial Z_k(x,y)}{\partial y}\Big|_m$$

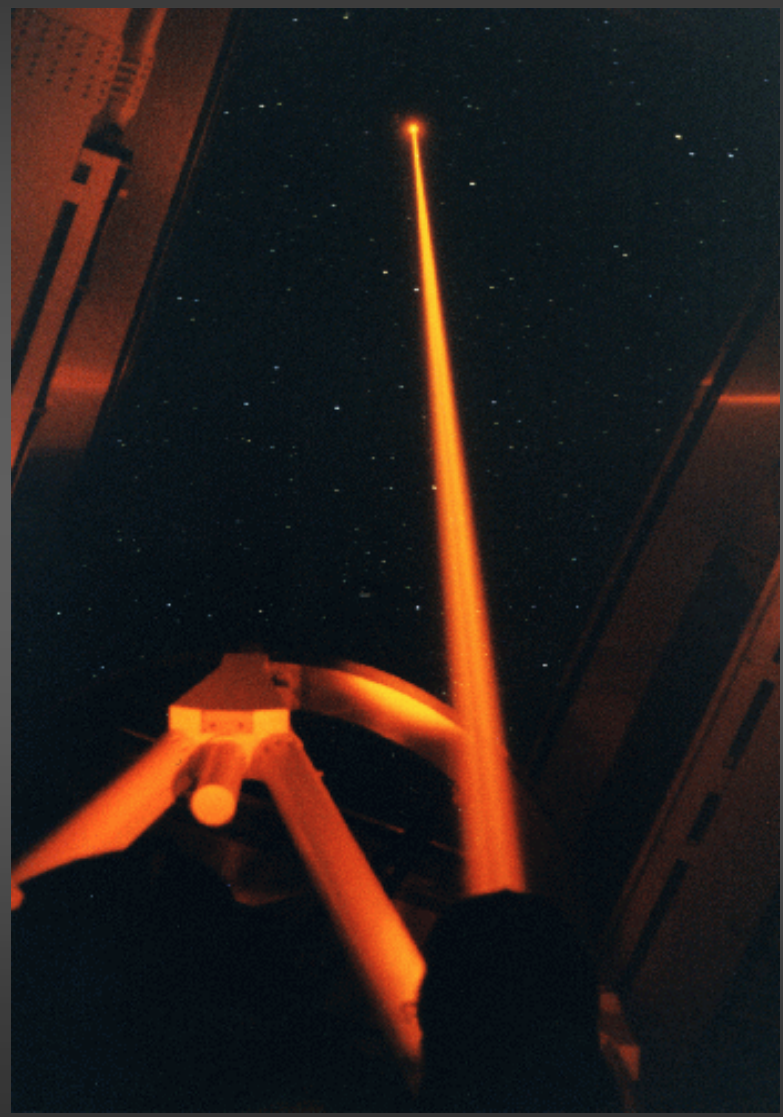
The model coefficients are obtained by inverting the matrix and calculating:

$$a = \left[(B^T B)^{-1} B^T\right] s$$

Calibration with an internal light source gives the mirror response matrix [G] and the actuator commands g:

$$g = [G]a$$

Adaptive Optics

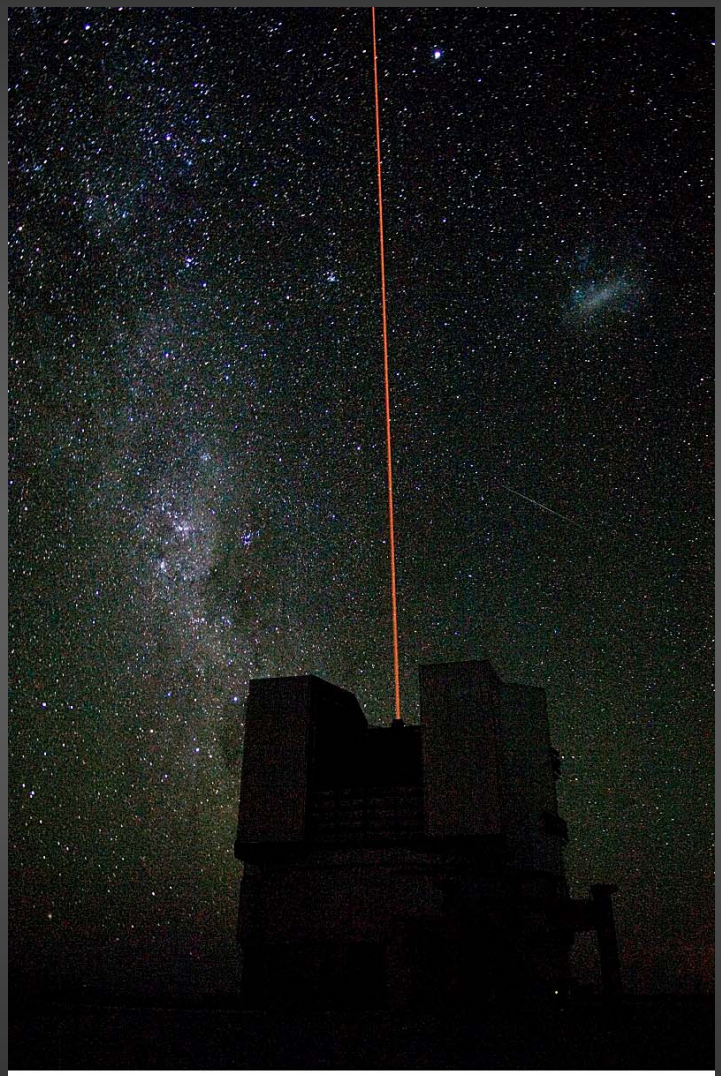


MPE laser guide star at the ALFA Calar Alto AO-System

Adaptive Optics at ESO Paranal

CONICA at
the VLT UT4

Adaptive Optics at ESO Paranal



First Light of the VLT Laser Guide Star

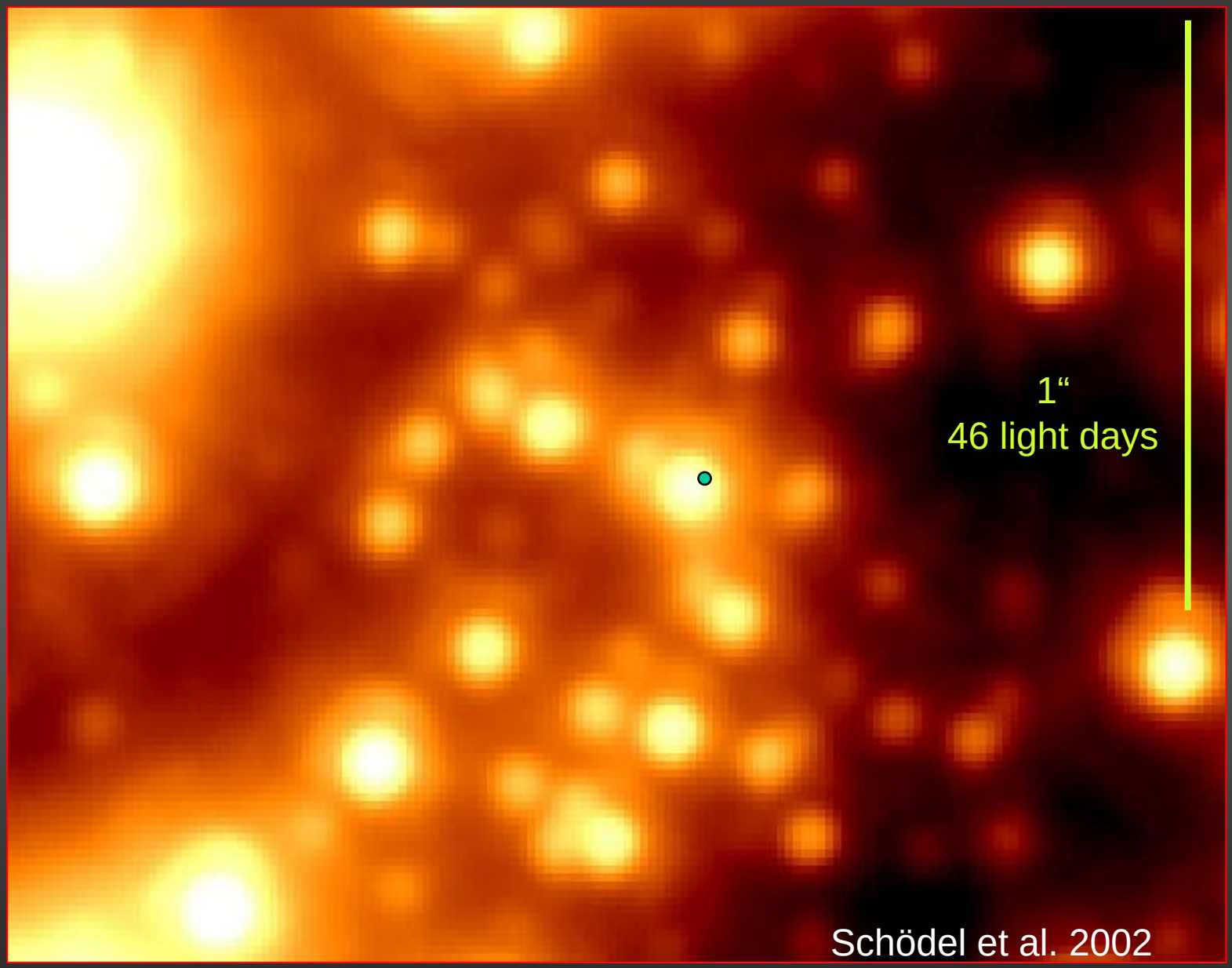
ESO PR Photo 07a/06 (23 February 2006) © ESO

An Artificial Star Above Paranal

ESO PR Photo 07b/06 (23 February 2006) © ESO

28 Jan. 2006; 8 W into a fiber

Adaptive Optics at the VLT in Chile



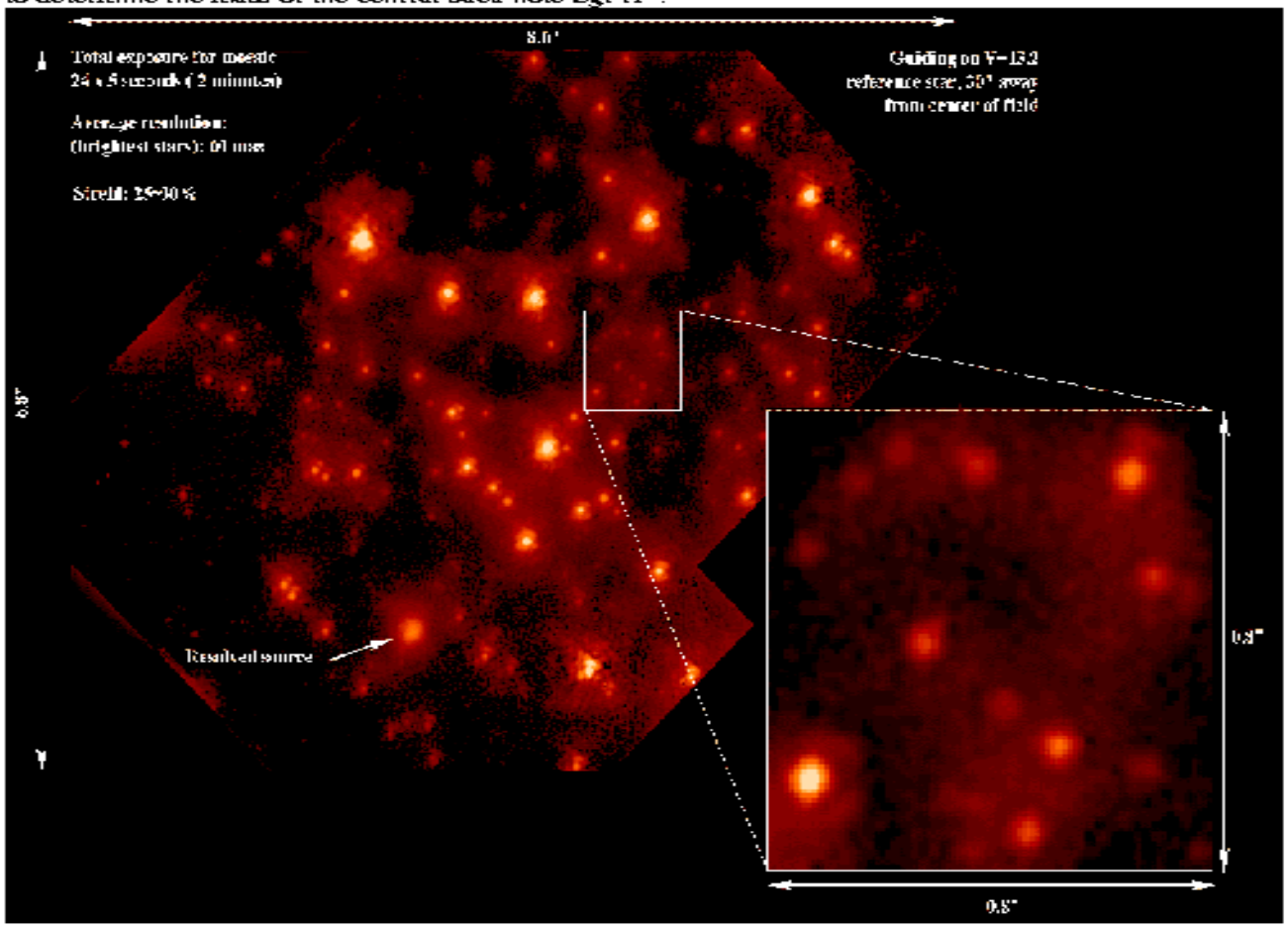
NACO
NIR
2μm

Keck II AO image of the GC

Adaptive Optics at Keck

Galactic Center
Keck Adaptive Optics

Mosaic of 24 images (total integration time: 120 seconds), this image shows the very central area of our own galaxy, the Milky Way. It was obtained on May 26th, 1999. The central arcsecond (inset) will help to determine the mass of the central back hole Sgr A*.



Position of the central mass from accelerations

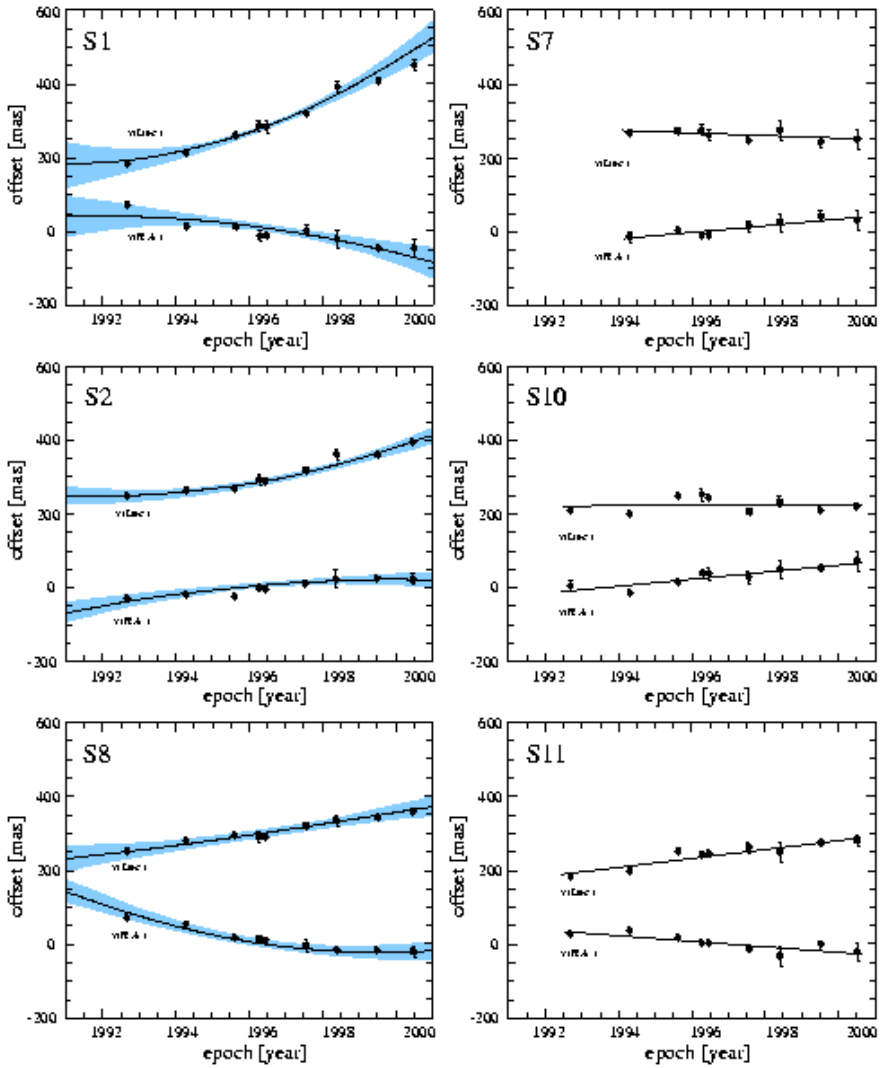
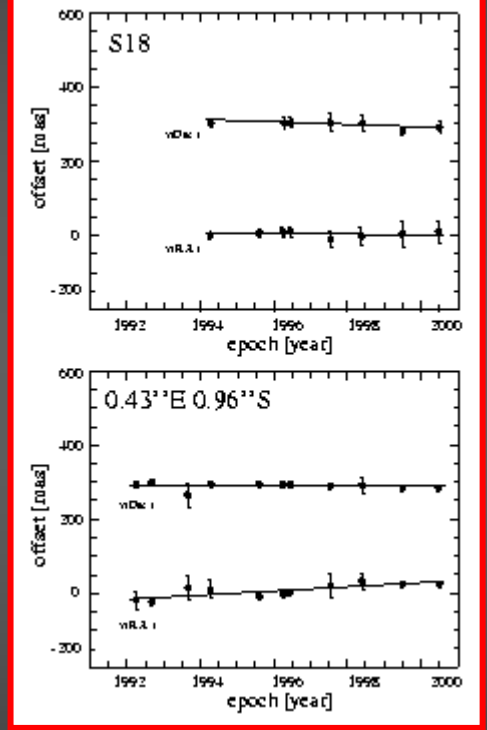

S1
S7
S2
S10
S8
S11
offset [mas]
epoch [year]
1992
1994
1996
1998
2000
600
400
200
0
-200

Fig.1


S18
0.43°E 0.96°S
offset [mas]
epoch [year]
1992
1994
1996
1998
2000
600
400
200
0
-200

The Galactic Center

Newtons law:

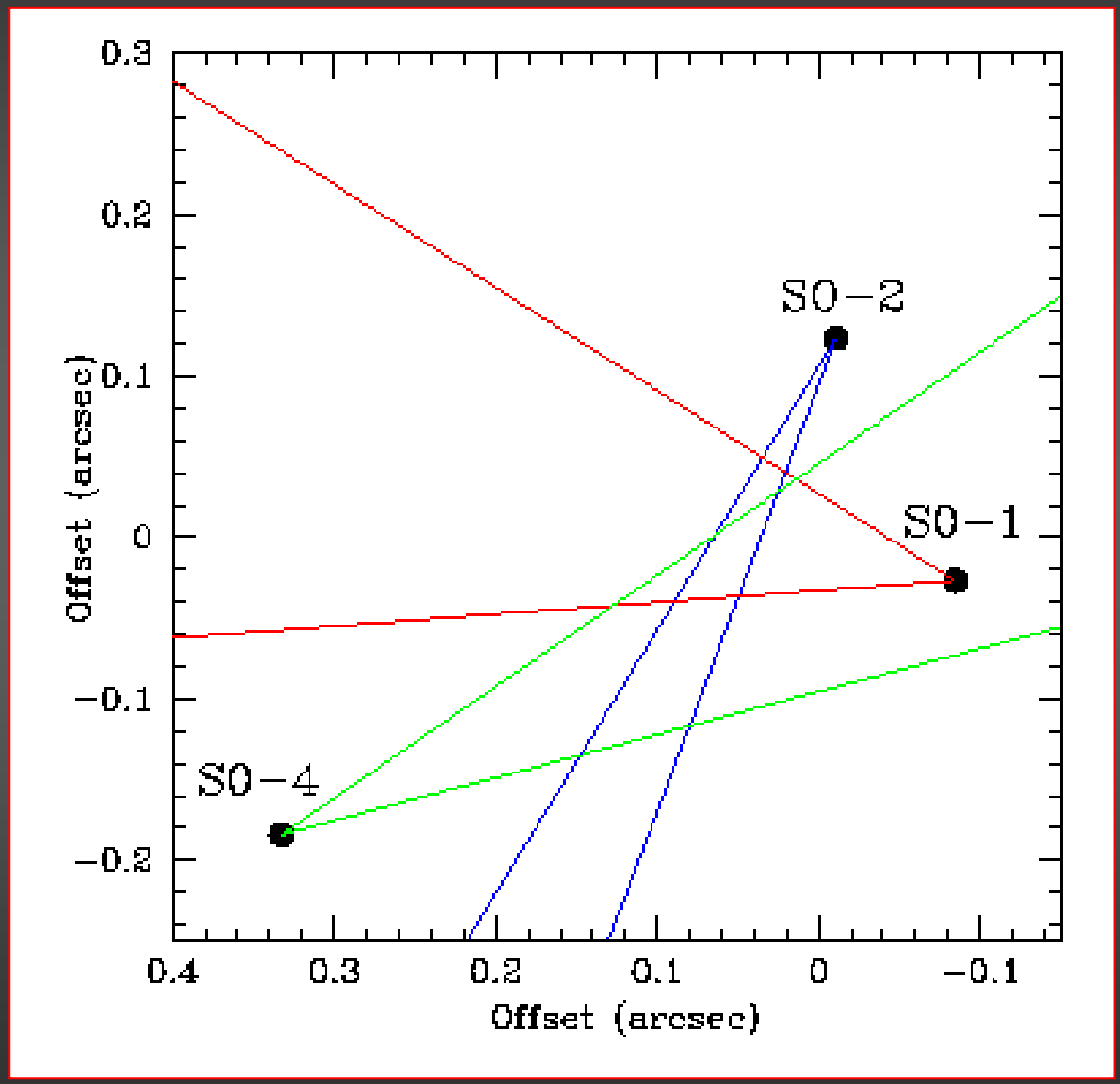
$$\vec{F} = m\vec{a} = -G\frac{Mm}{r^2}\frac{\vec{r}}{r}$$

Acceleration vector points towards mass center!

Mass estimate from accelerations:

$$M\cos^3(\vartheta) = 8681\frac{a[mas/yr^2]r^2[pc]}{G}$$

The Galactic Center



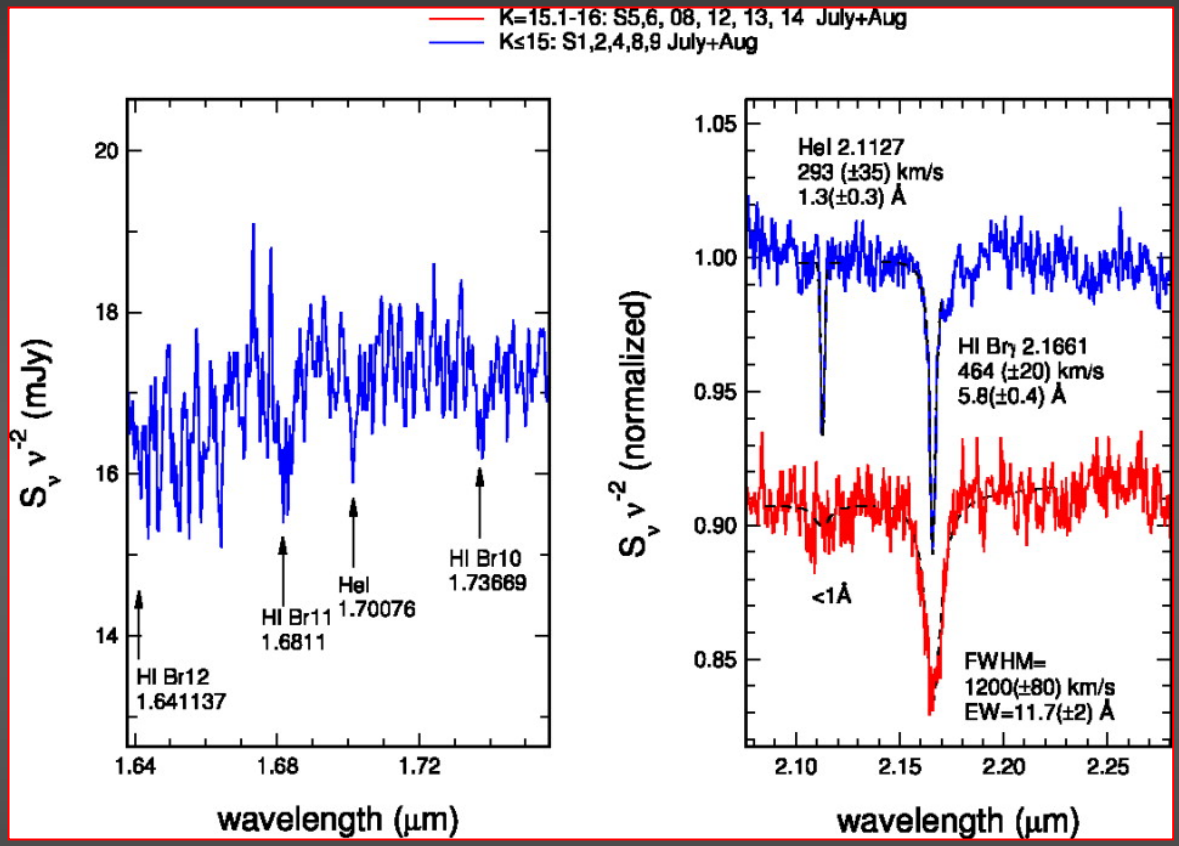
Acceleration vectors

SgrA* is included in the acceleration error cones of S1, S2, and S8.

Ghez , Morris, Becklin, Kremenek, & Tanner 2000, Nature 407, 349; astro-ph/0009339

Orbits of the central stars from multiple positions and velocities

High Velocity B-Stars in the Central Arcsecond



B0-B2 V stars

Brγ FWHM 460 km/s

HeI FWHM 293 km/s

R_{inst}~80 km/s

$\langle v_{rot} \sin(i) \rangle$=0.55 FWHM

=154 (+-19) km/s

Gathier, Lamers & Snow (1981): 130 km/s

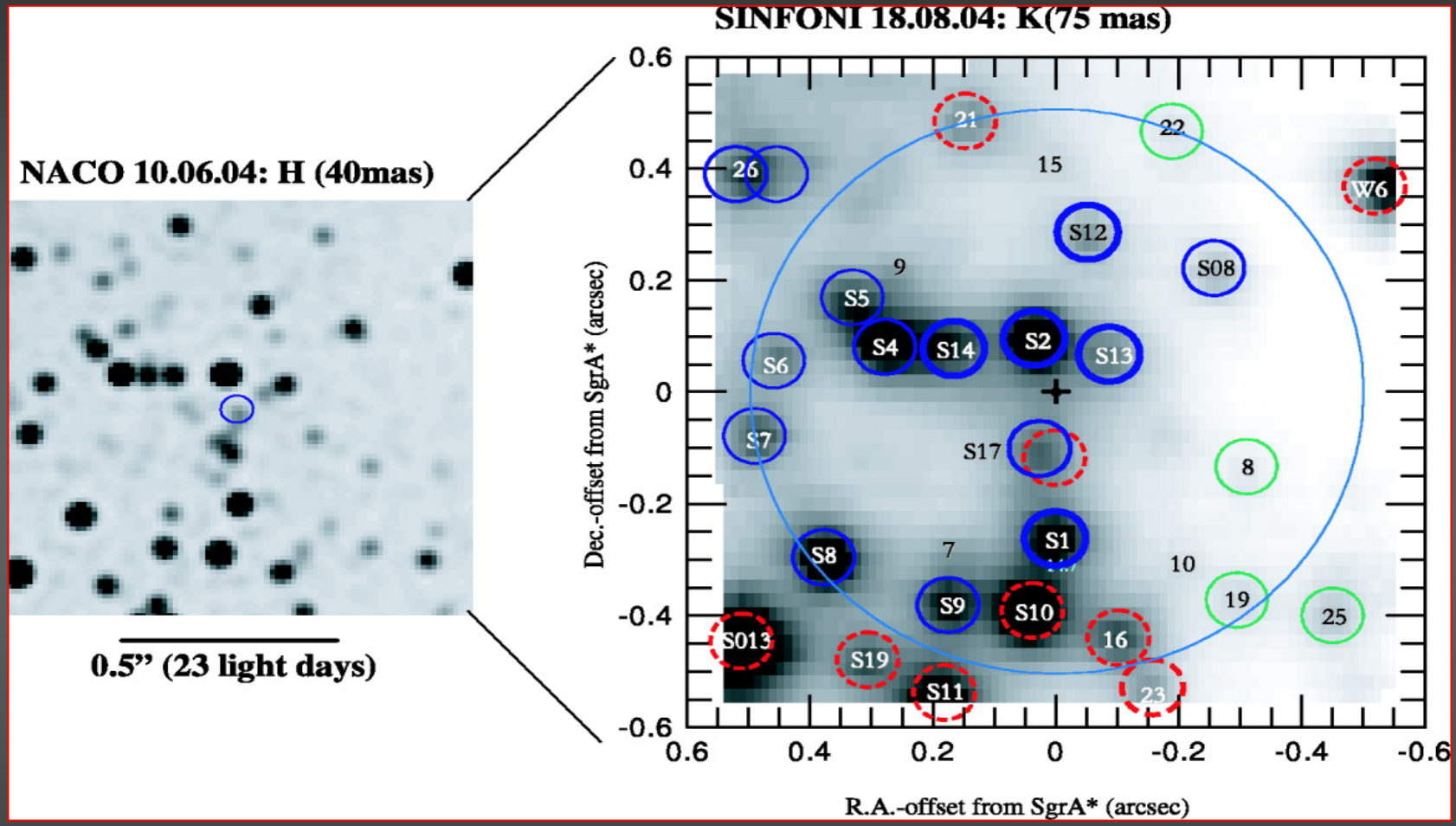
B4-9V stars

Brγ FWHM 1200 km/s

Eisenhauer et al. 2005

S-stars are normaly rotating B stars

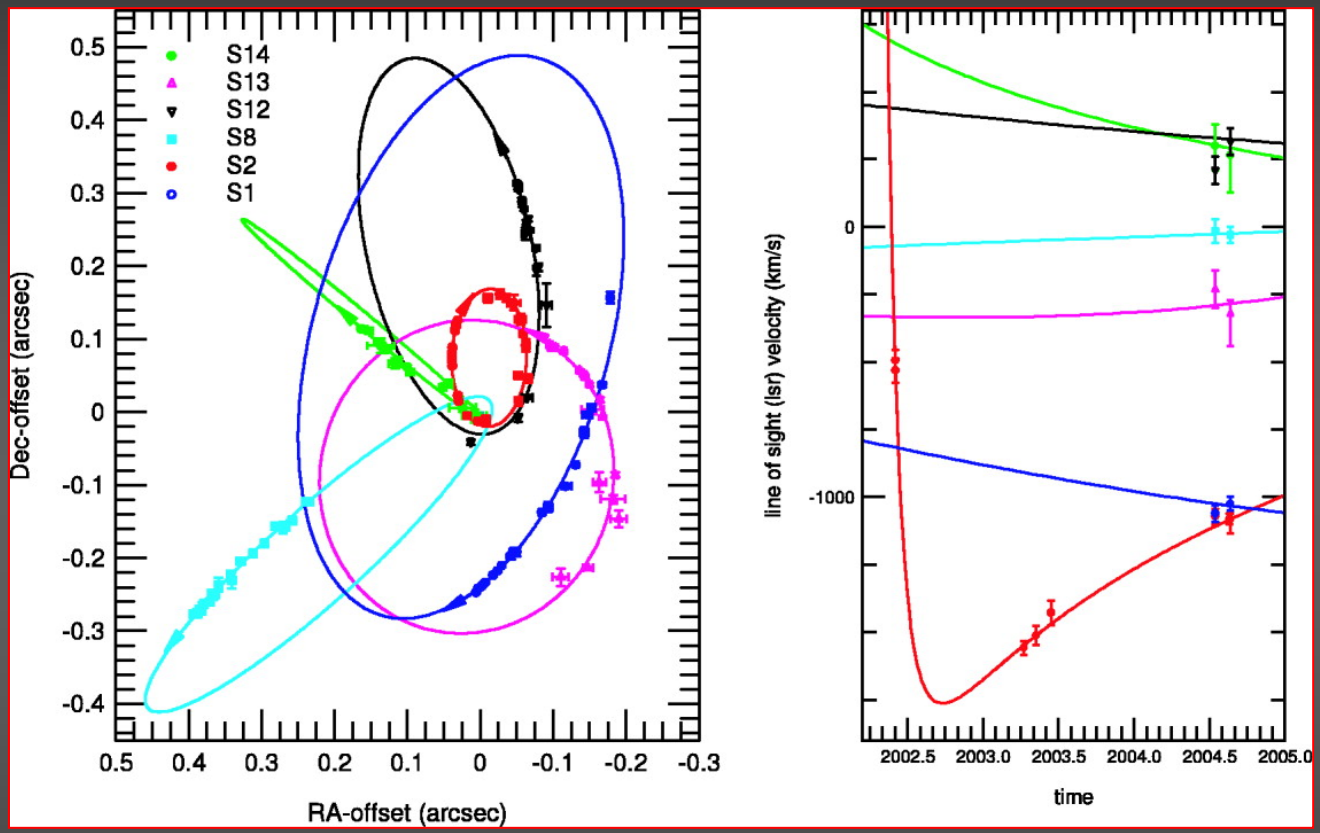
High Velocity Early Type Stars in the Central Arcsecond

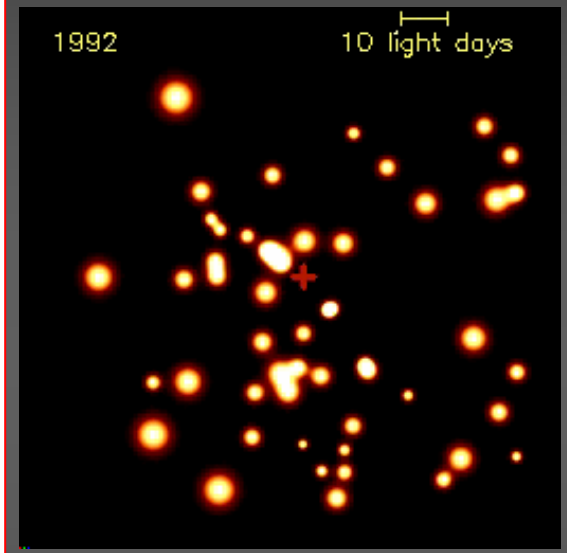


Eisenhauer et al. 2005

- late type
- early type
- uncertain but not late type

Orbits of High Velocity Stars in the Central Arcsecond





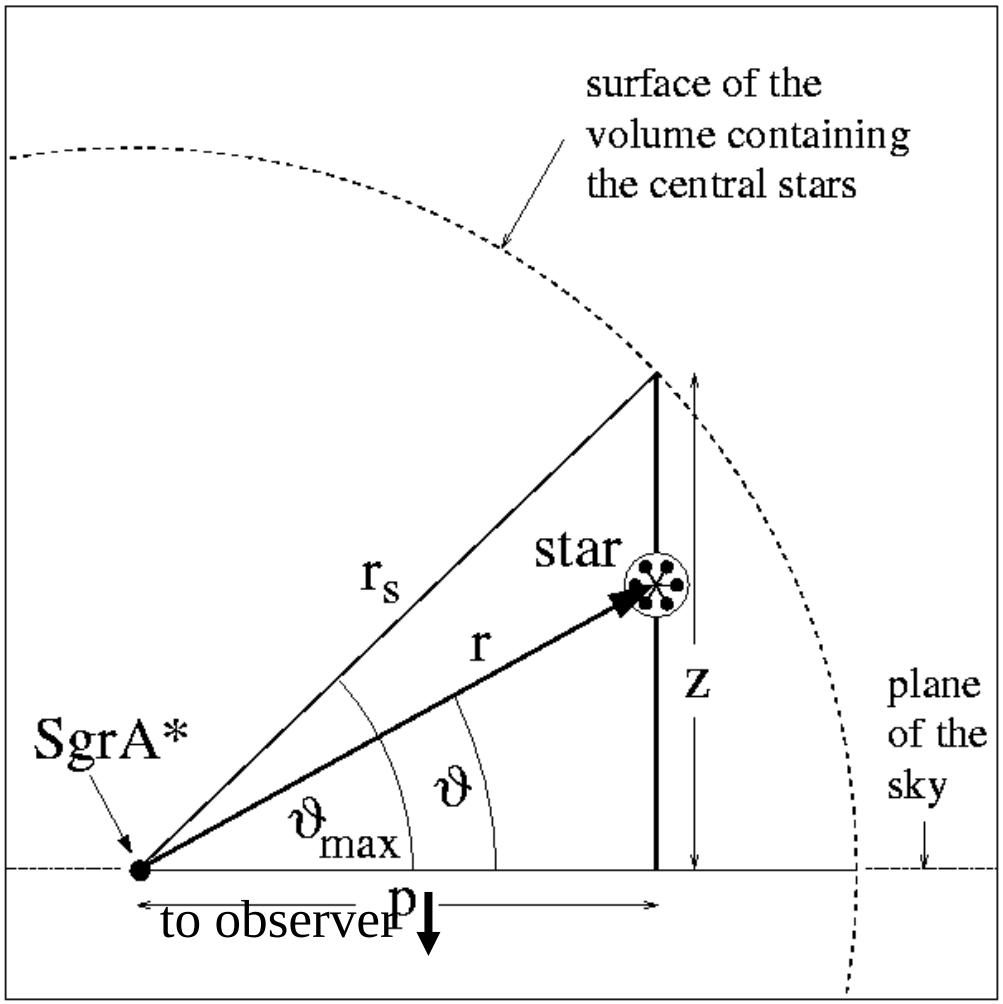
Eckart et al. 2002 (S2 is bound; first elements)
Schödel et al. 2002, 2003 (first detailed elements)
Ghez et al 2003 (detailed elements)
Eisenhauer 2005 (improved elements and distance)

*Mass of the BH at the position of SgrA**

Mass and mass distribution

Enclosed mass estimate from accelerations

The Galactic Center



Geometry for stars at the Galactic Center:

Projection of the acceleration vector onto the plane of the sky in which SgrA* is located.

$$P(V > v_{star}, R) =$$
$$1 - P(V < v_{star}, R) =$$
$$1 - \frac{1}{\sigma}\int_0^{v_{star}} v \times \exp\left(-v^2/\left(2\sigma^2\right)\right) dv$$

S1,S2,S8 are within a 15mpc (0.4“) radius sphere around SgrA*

The Galactic Center

Newtons law:

$$\vec{F} = m\vec{a} = -G\frac{Mm}{r^2}\frac{\vec{r}}{r}$$

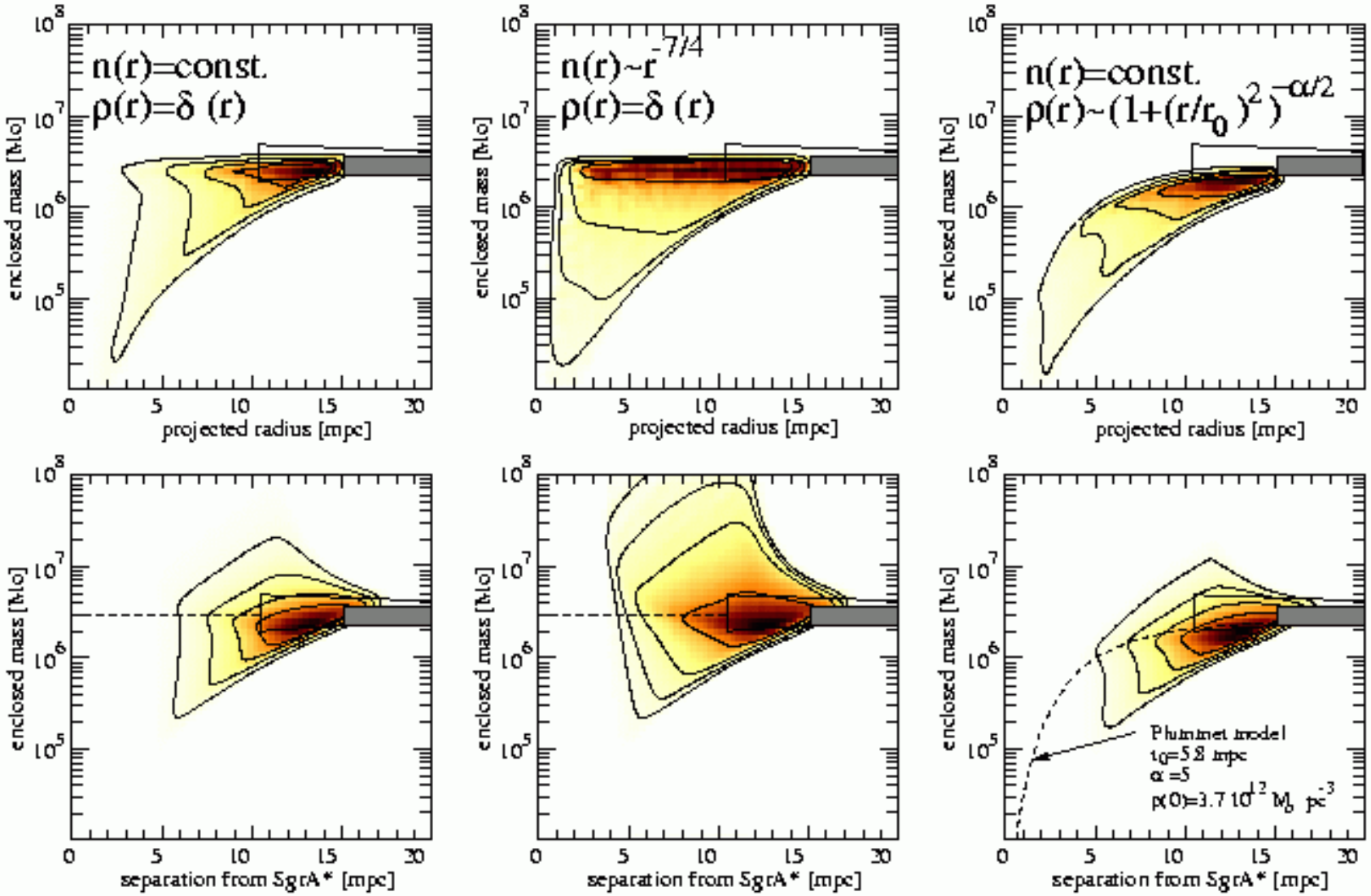
Acceleration vector points towards mass center!

Mass estimate from accelerations:

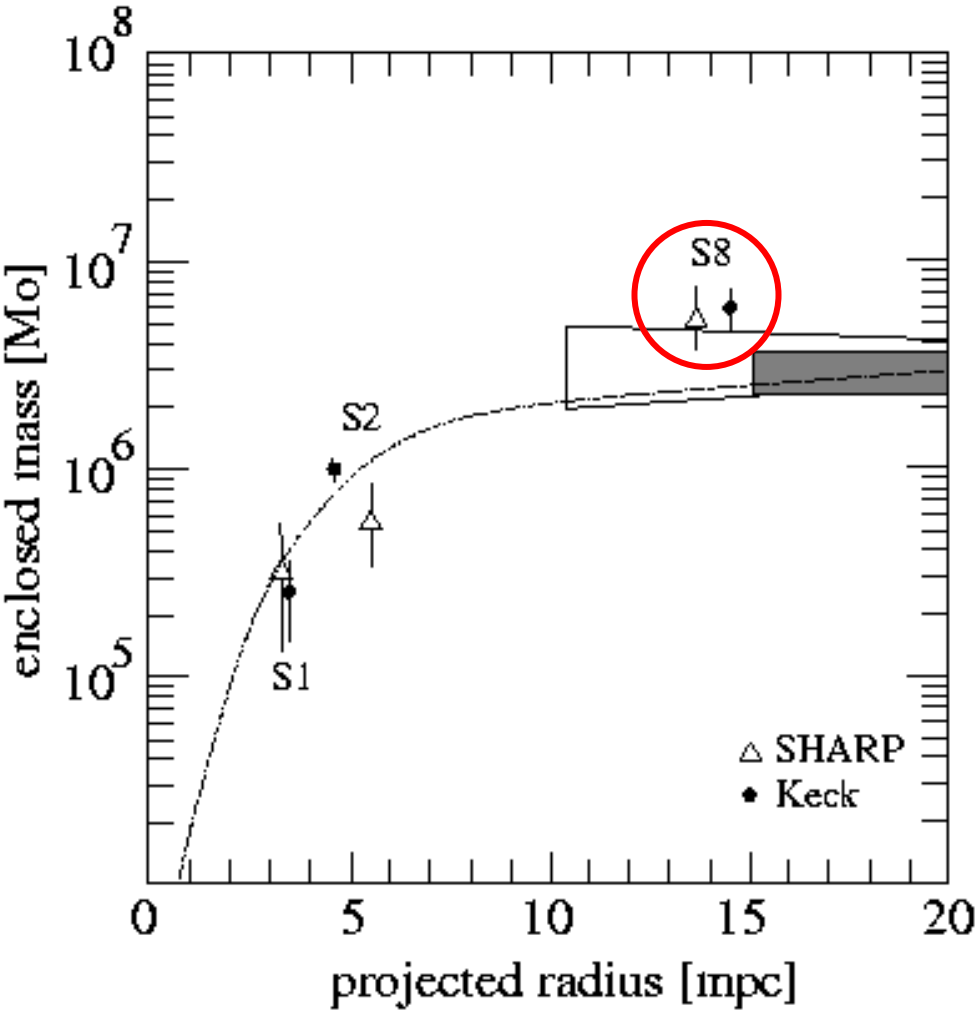
$$M\cos^3(\vartheta) = 8681\frac{a[mas/yr^2]r^2[pc]}{G}$$

The Galactic Center

Statistical deprojection of the radii and accelerations for a volume of 0.4‘‘+/-0.1‘‘



The Galactic Center

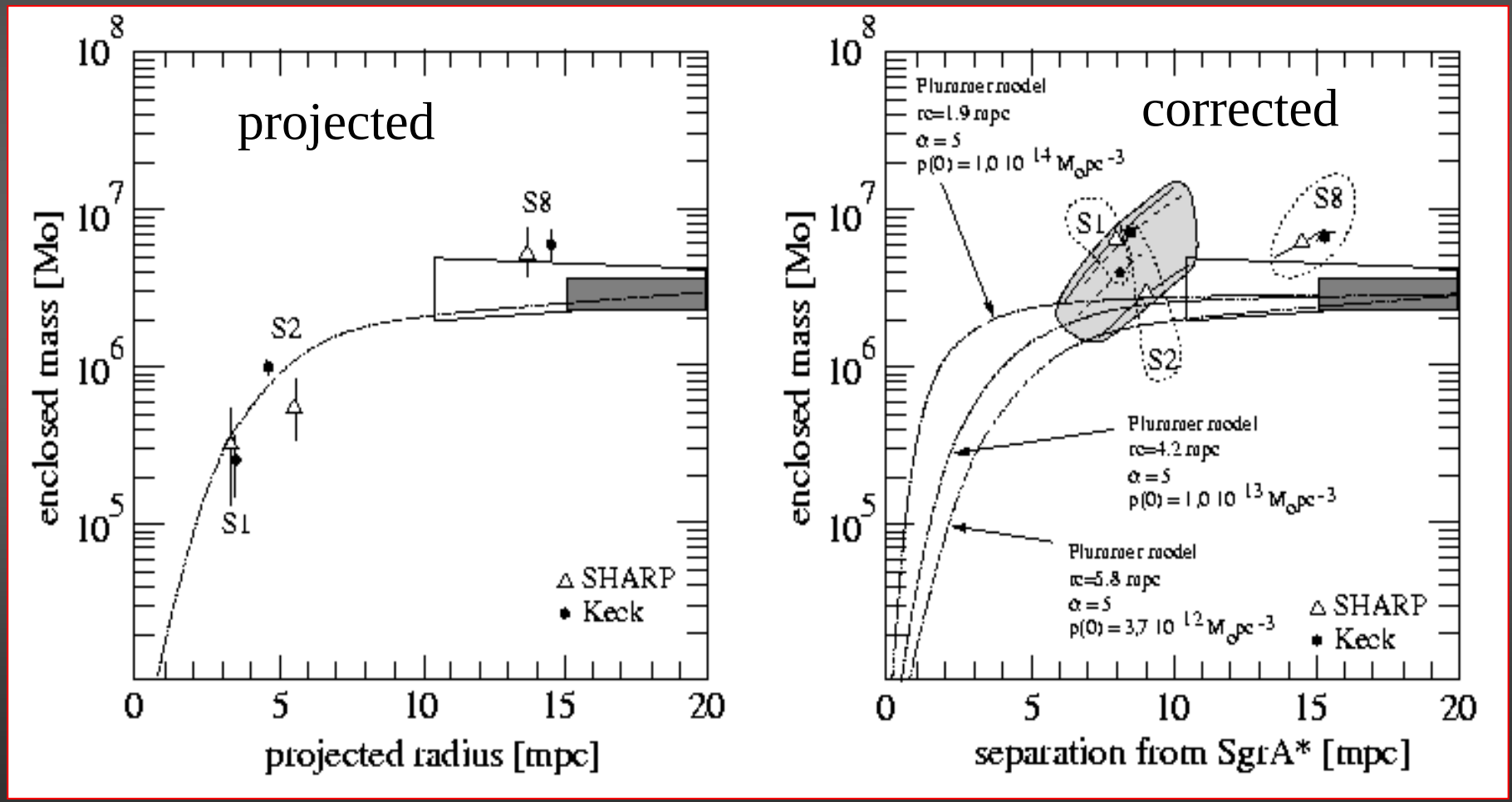


Projected enclosed mass estimates from projected radii and accelerations. These numbers are only lower limits of the actual enclosed mass!!

The enclosed mass estimate from the accelaration of S8 is currently too high.

The Galactic Center

Enclosed mass estimate based on accelerations



Mass Estimators

Enclosed Mass: First Order Estimates

Mass enclosed within projected radius p, assuming that the stars are just bound i.e. on ellipses:

$$E_{kin} = \frac{1}{2} m v^2 < G \frac{Mm}{p}$$

The minimum enclosed mass is then:

$$M_{\min}(< p) \geq \frac{v_{sky}^2 p}{2G}$$

For individual stars (few hundered km/s @ a few 10mpc distance) one then get of the order of 1000.000 solar masses.

Enclosed Mass: Mass Estimators

The mass estimator derived from the virial theorem assumes a homogenous distribution of stars and an isotropic velocity field:

$$M_{virial} = \frac{3\pi}{2G} \frac{\sum_i w(i) v_i^2}{\sum_i w(i) / p_i}$$

The mass estimator derived by Bahcall & Tremaine assumes that the stars are on isotropic orbits that are dominated by a central mass:

$$M_{BT} = \frac{16}{\pi G \sum_i w(i)} \sum_i w(i) p_i v_i^2$$

For the inner most ensamble of stars both estimators result in approximately 3 million solar masses with <10mpc.

Jean‘s Method

Jeans mass

Form the collisionless Boltzmann equation

$$\frac{\partial f}{\partial t} + v\nabla f + \nabla\Phi\frac{\partial f}{\partial v} = 0$$

With the stellar phase space density

$$f = f(t, r, v)$$

and a spherical system with

$$\sigma_\varphi^2(r) = \sigma_\vartheta^2(r)$$

One can deduce the Jeans Equation :

$$\Phi = \frac{GM(r)}{r} = v_{rot}^2(r) - \sigma_r^2(r)\left\langle \frac{d\ln(n(r))}{d\ln(r)} + \frac{d\ln(\sigma_r(r))}{d\ln(r)} + 2\beta \right\rangle$$

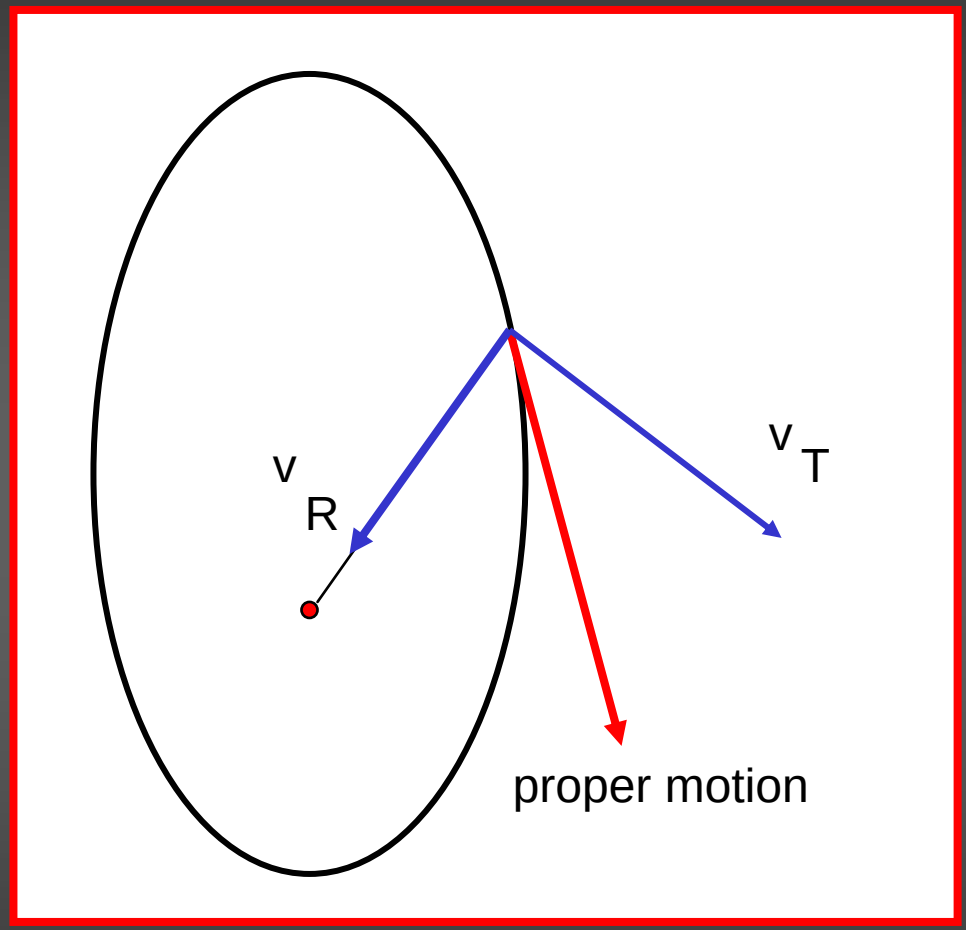
The Jeans-Mass

$$M(r) = f(v_{rot}(r), \sigma_r(r), n_r(r), \beta)$$

Contains ß as a measure for the anisotropy of the (3-dimensional) velocity field:

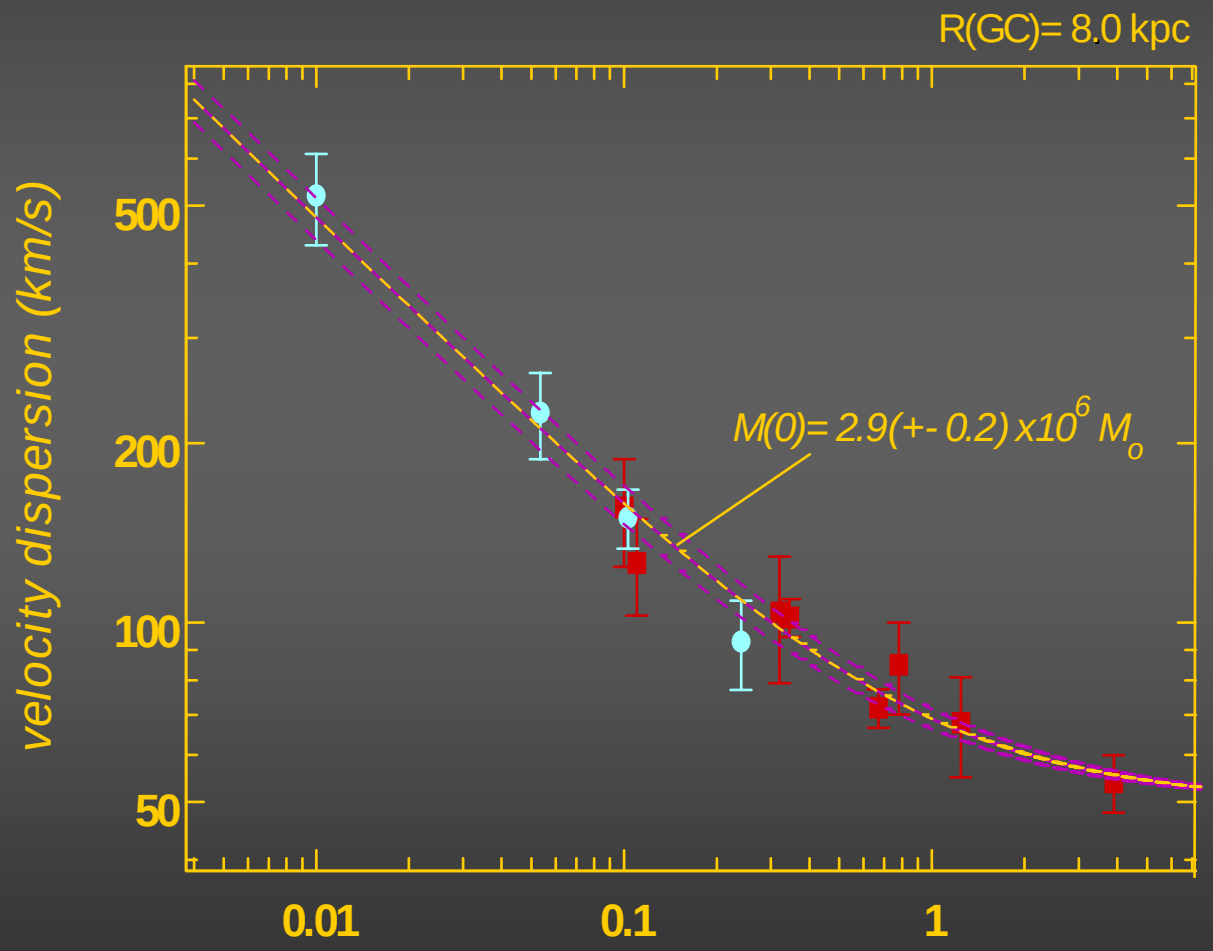
$$\beta = 1 - \frac{\sigma_\vartheta^2(r)}{\sigma_r^2(r)}$$

The Galactic Center



The observable projected velocity vector can be decomposed into velocity vectors in tangential T and radial R direction in the plane of the sky.

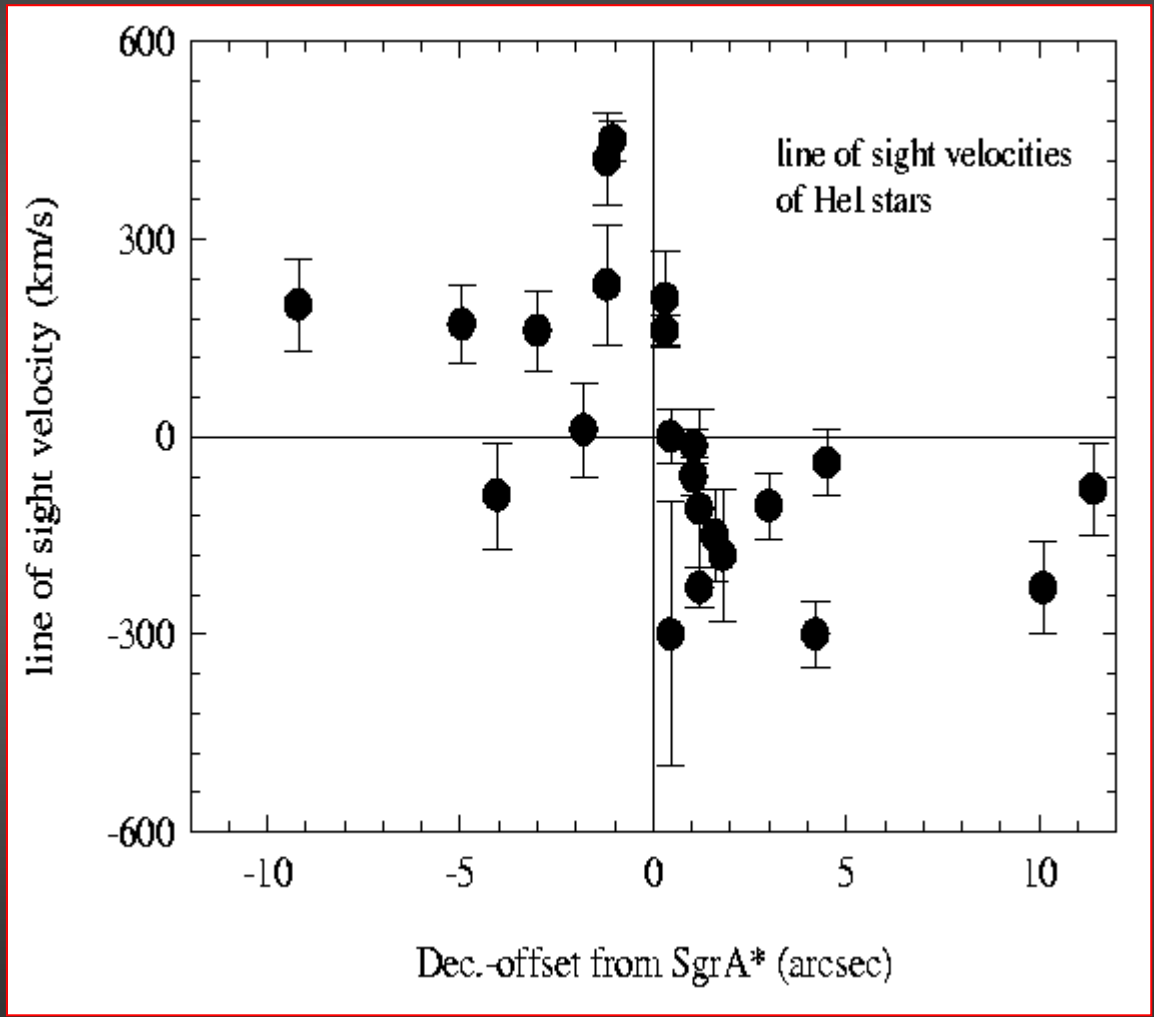
*Velocity as a function of separation from SgrA**



proper motions
radial velocities

Eckart, Genzel 1996,1997
Genzel et al. 1997

Counter rotation of the central stellar cluster in radial velocities

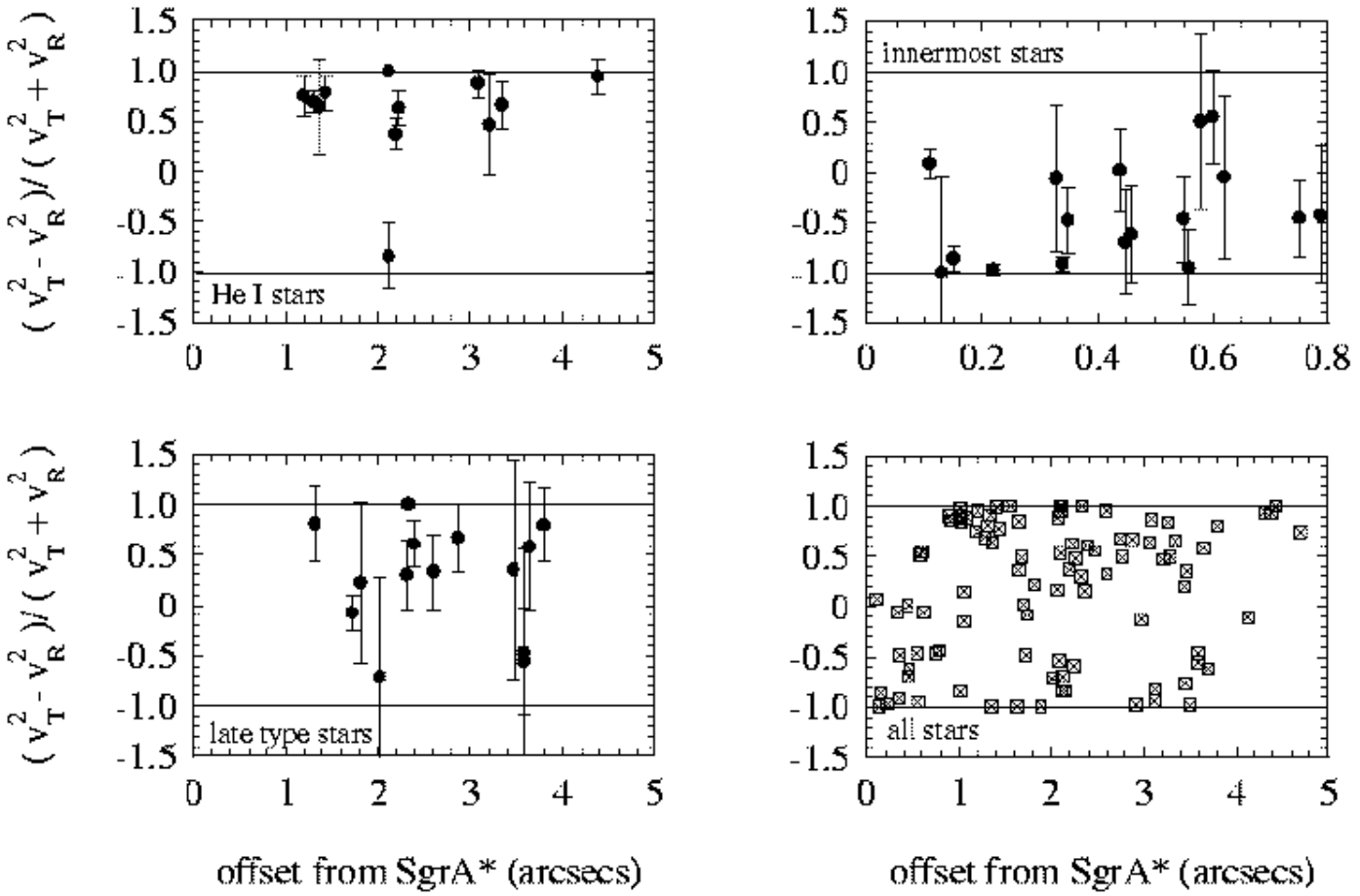


The Galactic Center

Indications for anisotropies in the proper motion velocity field

Genzel, Pichon, Eckart, Gerhard, Ott, 2000, MNRAS 317, 348

$$\gamma = (v_T^2 - v_R^2)/(v_T^2 + v_R^2)$$



The Galactic Center

$$\langle \beta \rangle = 1 - \frac{\langle \sigma_t^2 \rangle}{\langle \sigma_r^2 \rangle} = 3 \frac{\langle \sigma_R^2 \rangle - \langle \sigma_T^2 \rangle}{3\langle \sigma_R^2 \rangle - \langle \sigma_T^2 \rangle}$$

The anisotropy measure β is defined via 3-dimensional velocity dispersions (tangential t and radial r). It has, however, been show how it is linked to observable projected velocity disperions of motions in tangential T and radial R direction in the orbits projectedonto the plane of the sky (Leonard & Merritt 1989).

The Galactic Center

The projected velocity dispersion σ(R) and surface density Σ(R) are linked to the 3-dimensional quantities n(r) and σ(r) via Abel integral equations.

$$\Sigma(R) = 2\int_r^\infty n(r) r dr / \sqrt{(r^2 - R^2}$$

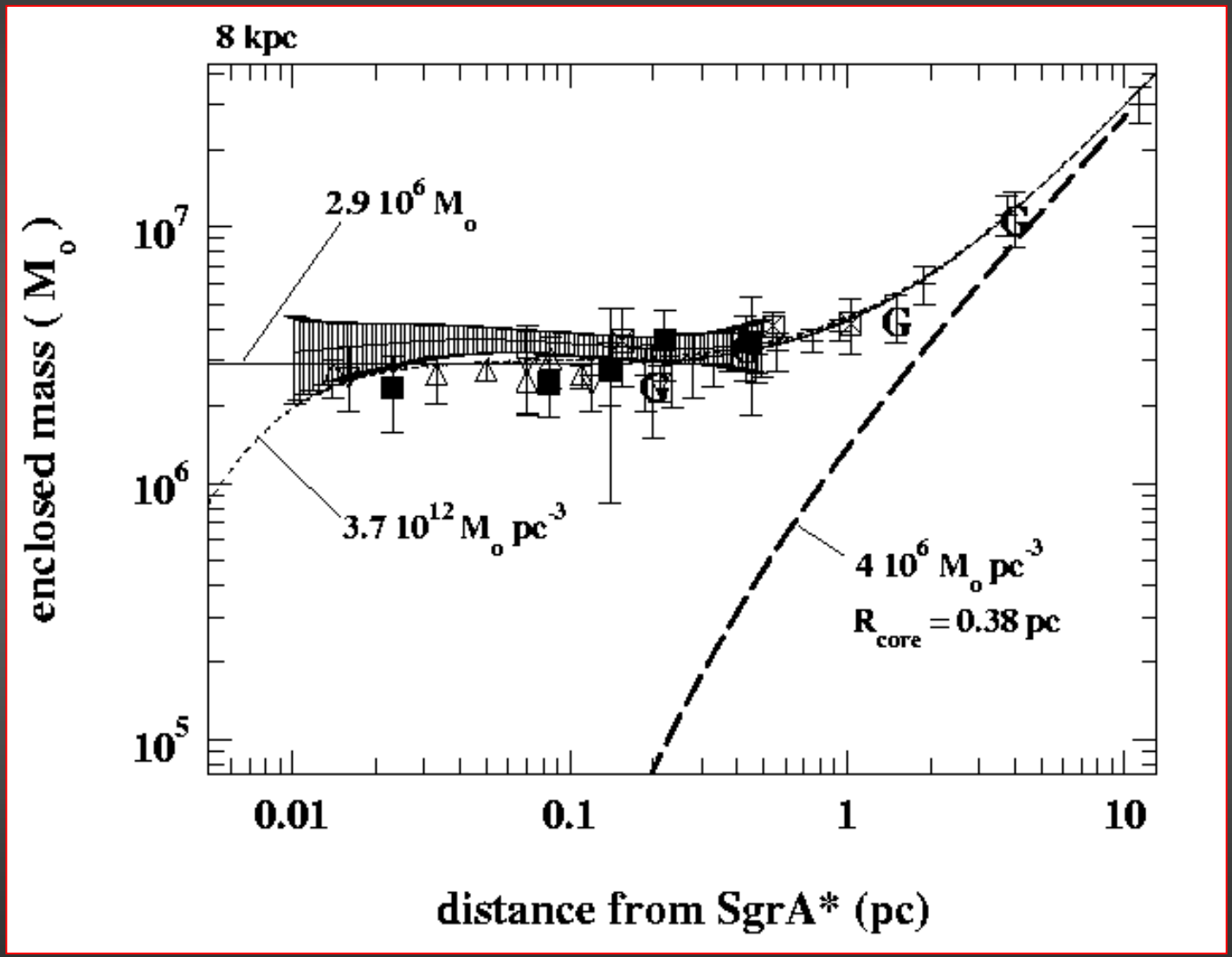
$$\Sigma(R)\sigma_R(R)^2 = \int_r^\infty n(r)\sigma_r(r)^2 r dr / \sqrt{(r^2 - R^2)}$$

The 3-dimensional quantities n(r) and σ(r) can be modeled via analytical expressions in the target space to fit the data in the observer space via the Abel integral equations .

$$n(r) = (\Sigma_o / r_o)[1 + (r / r_o)^\alpha]^{-1}$$

$$\sigma_r(r)^2 = \sigma(\infty)^2 + \sigma(r_0)^2 (r / r_0)^{-2\varepsilon}$$

Enclosed mass towards the center of the Galaxy



The Galactic Center

With a spherical potential

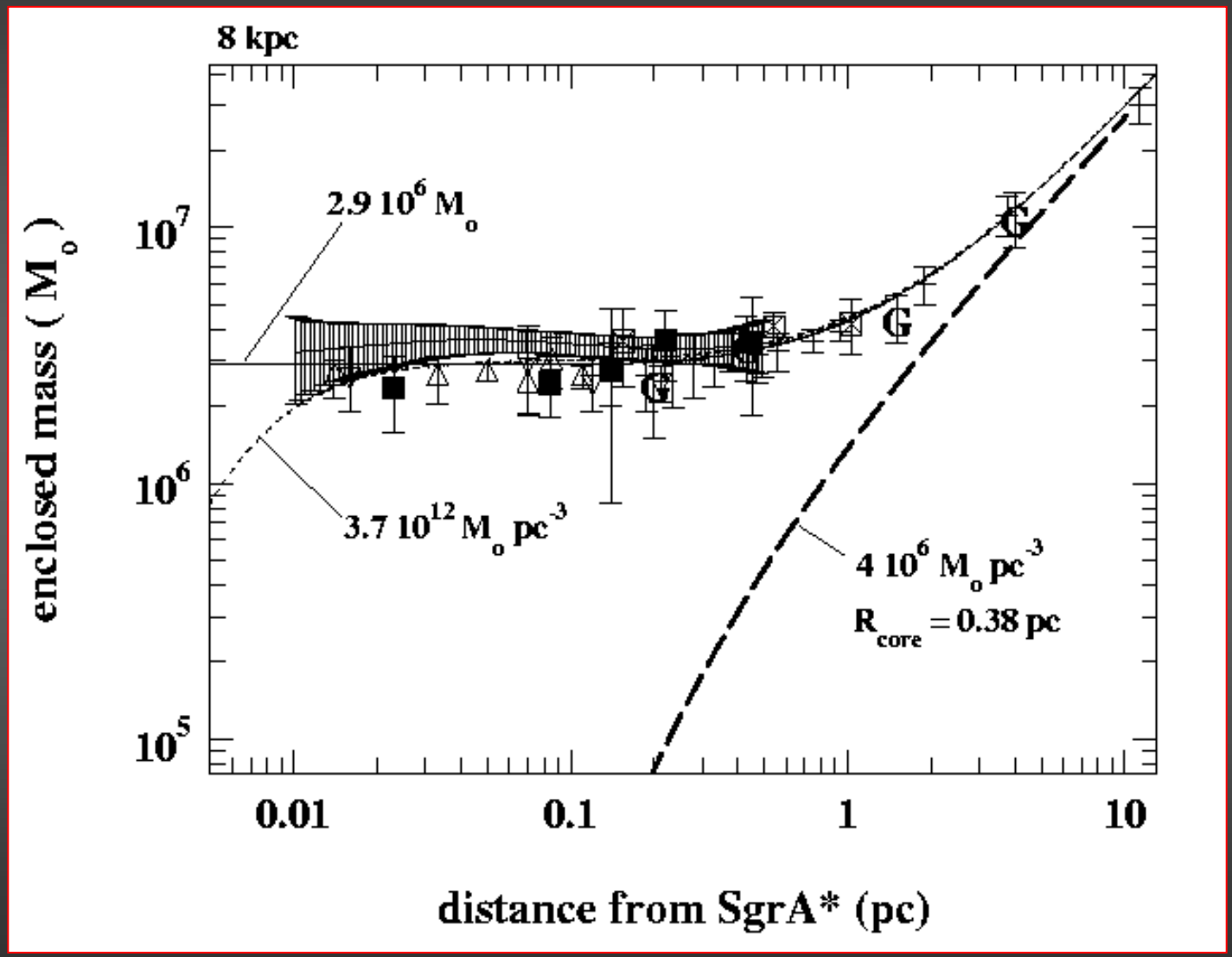
$$\Phi = -\frac{GM}{\sqrt{(r^2 + b^2)}}$$

one finds for shperical stellar systems a volume density

$$\rho = \frac{\rho_0}{(1+(r/b)^2)^{5/2}}$$

aslo called Plummer model (Plummer 1911)

Enclosed mass towards the center of the Galaxy



Mass and mass density for SgrA*

With

$$M_{SgrA*} \approx 3.0 \times 10^{6} M_{o}$$

follows

$$\rho_{SgrA*} \geq 4 \times 10^{12} M_{o}\, pc^{-3}$$

This has to be compared with the mass density of a 3 Millionen Mo black hole within a Schwarzschild sphere of 8x10^{11} cm diameter:

$$\rho_{SgrA*} \geq 4.4 \times 10^{25} M_{o}\, pc^{-3}$$

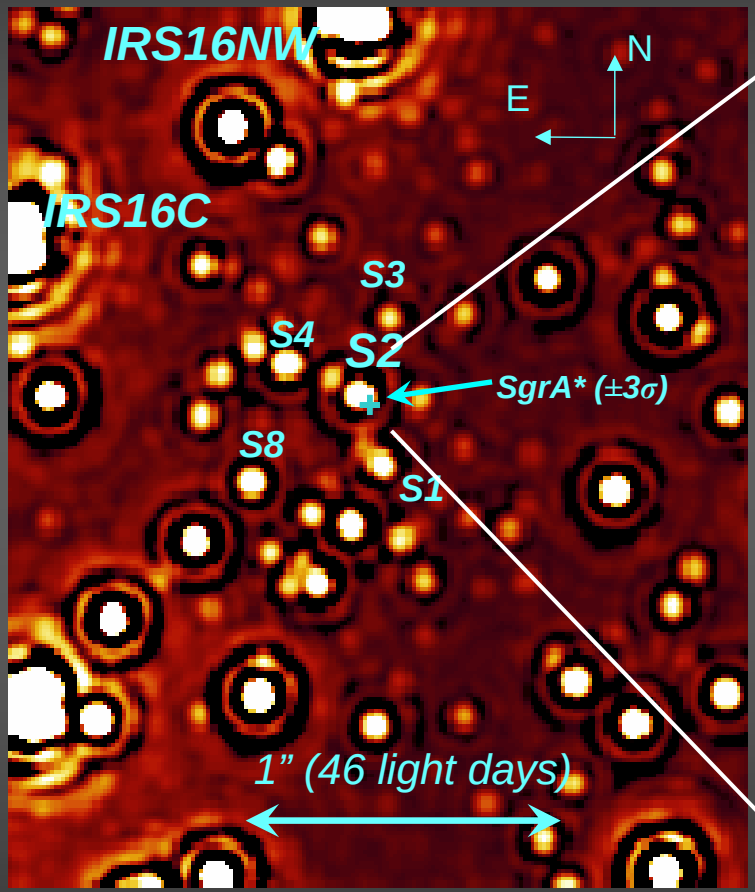
Derived from stellar statistics within the central few arcseconds.

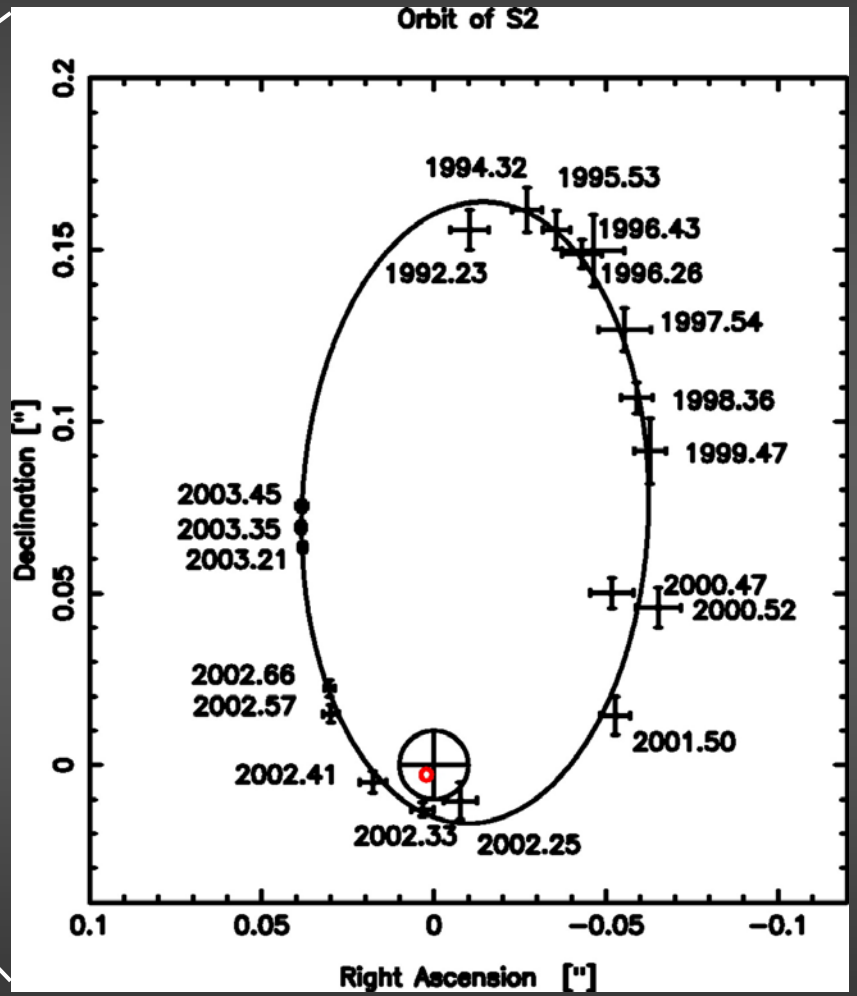
Genzel, Eckart, Ott, Eisenhauer 1997
Ghez, Klein, Morris, Becklin 1998
Eckart, Ott, Genzel 1999
Genzel et al. 2000

Mass from the S2 Orbit

Mass and mass density from a single star!

The Orbit of S2 near SgrA*





Schödel, Genzel, Eckart, Ott, Reid, Alexander et al., Nature 419, 694, 2002
Eisenhauer et al. 2004, ApJ 597, L121, 2004

Enclosed Mass from S2 Orbit

Kepler‘s laws give

$$M_{S2} = \frac{4\pi^2}{G}\frac{a^3}{T^2}$$

For an orbital period T and a semi major axes a.

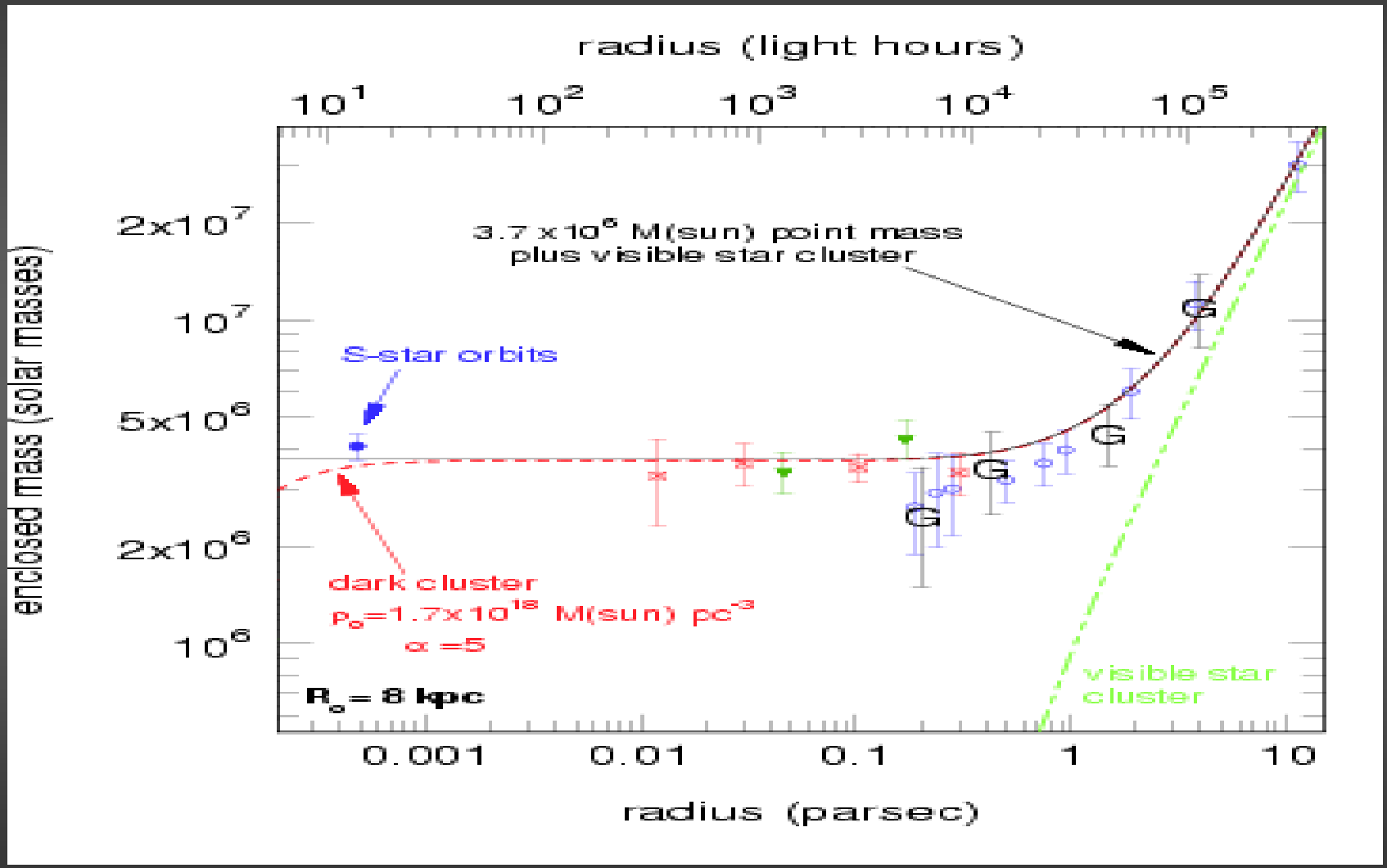
For S2 this results into:

$$M_{SgrA*} \approx (3.61 \pm 0.32) \times 10^6 M_o$$

One can solve for the distance at the same time: 7.62+/-0.32 kpc

Eisenhauer et al. 2005

Unresolved Enclosed mass



see Genzel et al. 1996, 2000, Eckart et al. 2002, Schödel et al. 2002, 2003

Mass and mass density for SgrA* from the Recent S2 Orbit

$$M_{SgrA*} \approx (3.6 \pm 0.3) \times 10^{6} M_{o}$$

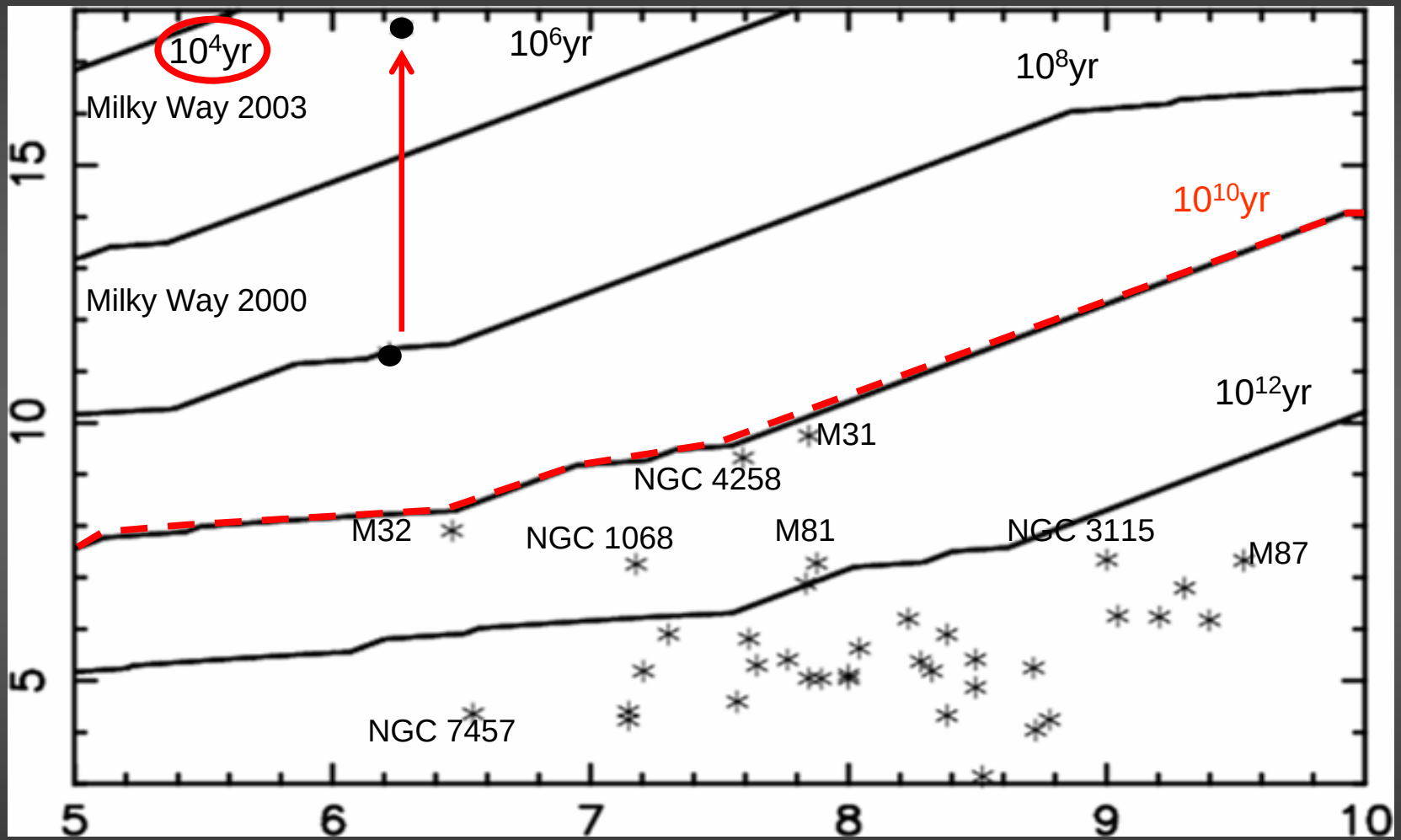
$$\rho_{SgrA*} \geq 10^{17} M_{o}\, pc^{-3}$$

This has to be compared with the mass density of a 3 Millionen Mo black hole within a Schwarzschild sphere of 8x10 ^{11}cm diameter:

$$\rho_{SgrA*} \geq 4.4 \times 10^{25} M_{o}\, pc^{-3}$$

Schödel et al. 2002
Eckart et al. 2002
Genzel, Eckart, Ott, Eisenhauer 1997
Ghez, Klein, Morris, Becklin 1998
Eckart, Ott, Genzel 1999
Genzel et al. 2000

Stability of Enclosed Masses

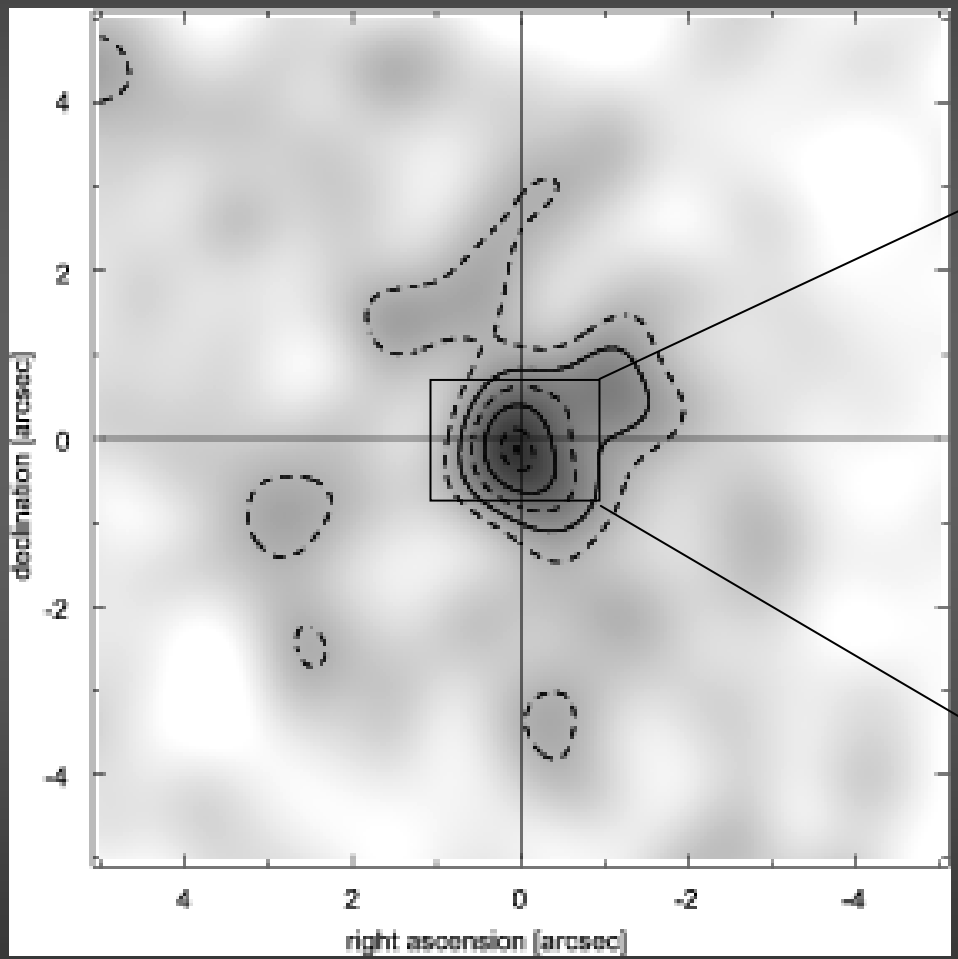


Maoz 1998;
Eckart, Schödel & Straubmeier 2004

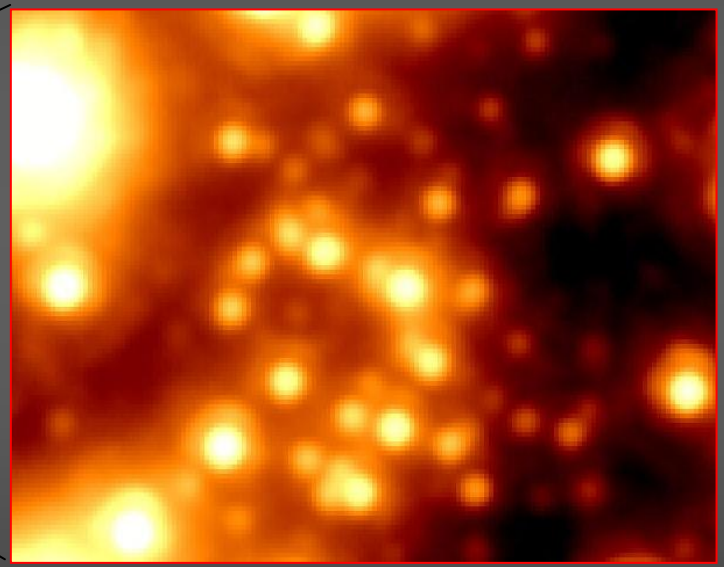
Stellar Mass of the Cusp

Distribution of stars: The central cusp

- More than 90 sources can be detected in the central arcsecond in H-Band NACO/VLT images!
- A stellar cusp is clearly detected.



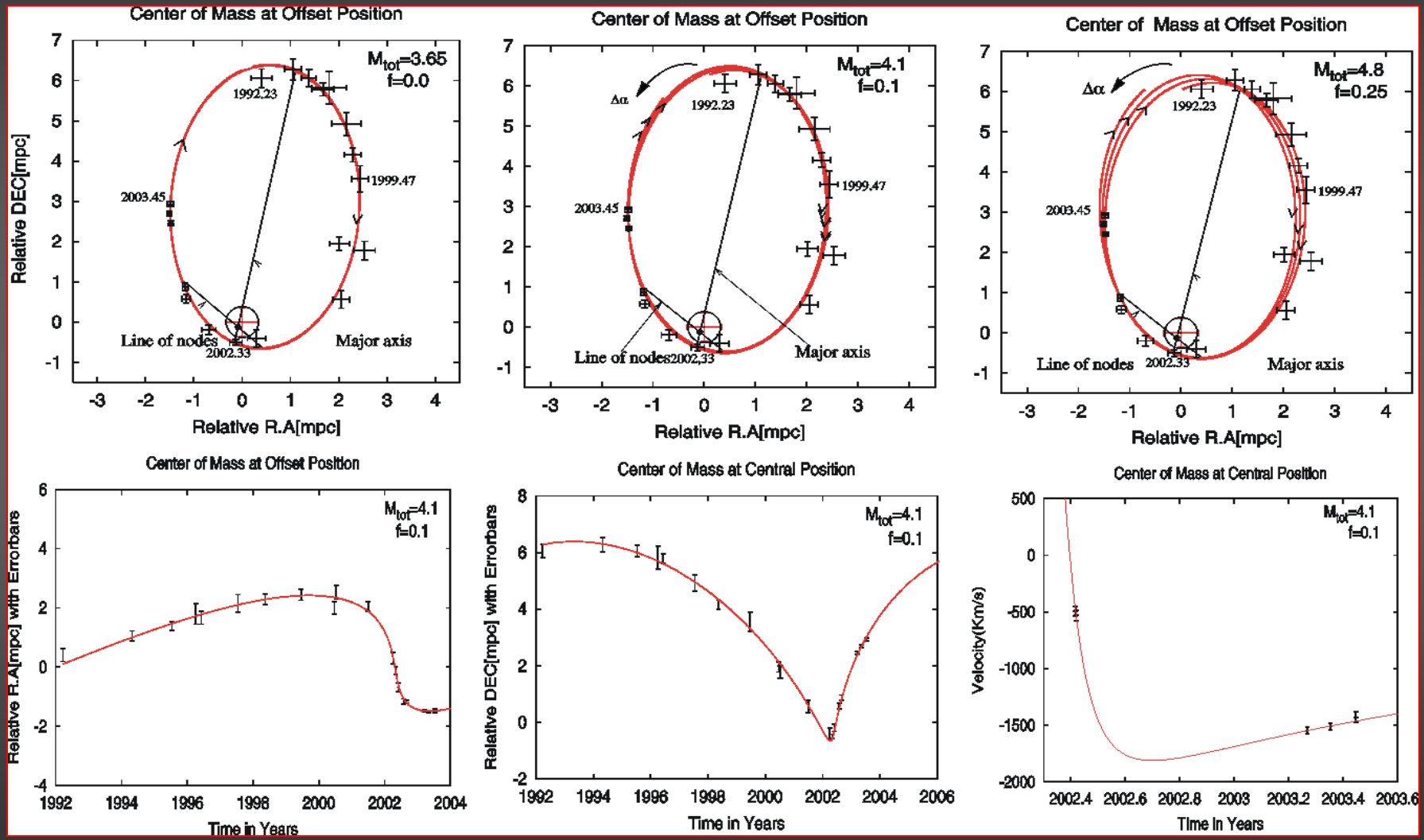
surface number density of stars
excess above mean density by 2, 3, 4, 5, 6.3 σ



1“/46 light days

Schödel et al. 2003
Eckart, Schödel, Straubmeier 2005

Weighing the central cusp



Mouawad, Eckart et al. 2003, 2005
Rubilar & Eckart A&A, 2001

cusp mass limit ~10**5 M_{solar}

End of Part I

Standard Accretion Theory

A conveniant way to describe the emission from the surroundings of a back hole is the so called Eddington luminosity.

The Eddington limit on the luminosity L of an object of mass M is set by the balance of gravity and radiation pressure in the object‘s envelope in the case of spherical accretion.

At a distance r from the center of the object the energy flux is

$$f = \frac{L}{4\pi r^2}$$

$\sigma_t f / c$

with the Thomson cross section σ_t

Standard Accretion Theory

If the envelope is bound to the object then the radiation pressure is balanced by gravity. For one proton with mass m_p per electron in the fully ionized material of the envelope, the balance condition is:

$$\frac{\sigma_t L}{4\pi c r^2} = \frac{GMm_p}{r^2}$$

The corresponding luminosity is called the Eddigton luminosity

$$L_{Edd} = \frac{4\pi GMm_p c}{\sigma_t} = \frac{4\pi cGM}{\kappa}$$

With $\sigma_t = 6.65\times10^{-25} cm^2$

and $m_p = 1.67\times10^{-24} g$

the opacity due to electron scattering is

$$\kappa = \frac{\sigma_t}{m_p} = 0.4 cm^2 g^{-1}$$

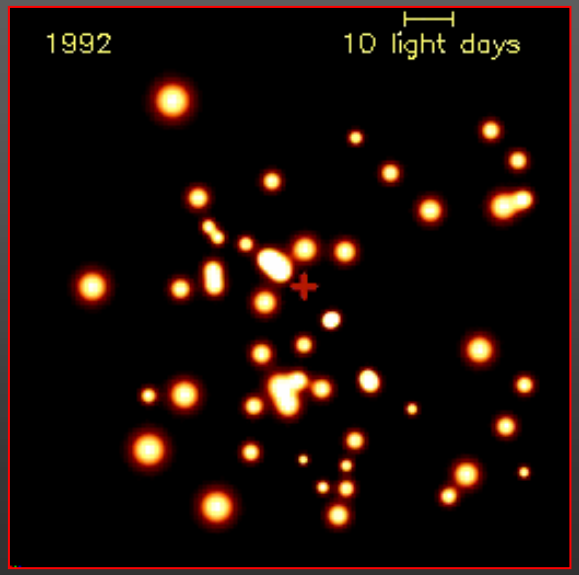
SgrA* at the Center of the Milky Way

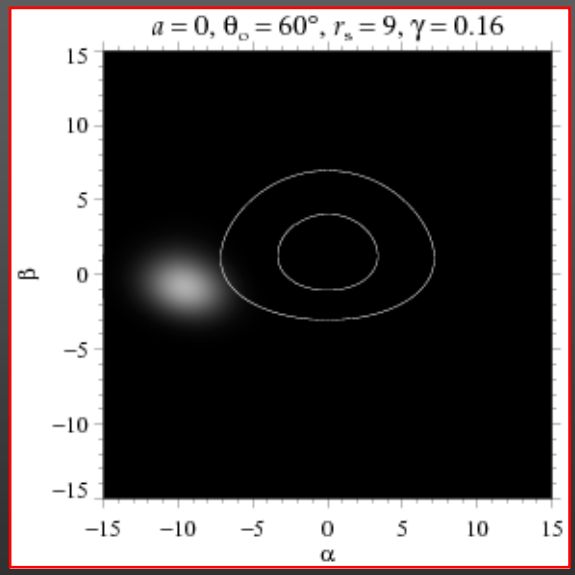
Observing the X- and γ-ray Sky

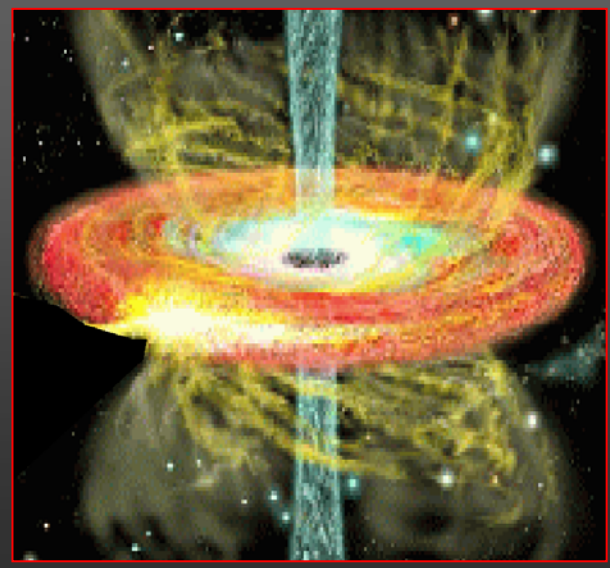
Astrophysical Spring School, April 2006

Andreas Eckart

I.Physikalisches Institut der Universität zu Köln







- II.Part

Accretion of matter onto SgrA*
Radio, X-ray variability
NIR/X-ray correlations
Adiabatic expansion
NIR polarization
Disk and jet models
Alternative models for SgrA*
IMBHs
MBHs in external galaxies

Future Experiments

The Accretion of Matter

Standard Accretion Theory

A back hole of mass $M = mM_{\odot}$

accrets at a rate $\dot{M} = \dot{m}\dot{M}_{Edd}$

Here $\dot{m}$ is the accretion rate expressed in units $\dot{M}_{Edd}$, the accretion rate at the Eddington luminosity

$$\dot{M}_{Edd} = \frac{L_{Edd}}{c^2 \eta_{eff}} = \frac{4\pi G(M / M_{\odot})}{\eta_{eff} \kappa c}$$

For $\eta_{eff} = 0.1$ this results in an accretion rate of

$$\dot{M}_{Edd} = 1.39 \times 10^{18} g s^{-1} = 2.21 \times 10^{-8} \left(\frac{M}{M_{\odot}} \right) M_{\odot} yr^{-1}$$

Standard Accretion Theory

With an estimated total wind mass loss - that could be accreted - of

$$\dot{M} \approx 2\times10^{-4} M_{\odot} yr^{-1}$$

that corresponds to an accretion rate in Eddington units of

$$\dot{m} \approx 1\times10^{-3}$$

for a black hole mass of $(3-4)\times10^{6} M_{\odot}$

From the 2.2 micron flux of ~2mJy one obtains a specific luminosity of

$$L = \nu L_{\nu} = 2.1\times10^{34} erg/s$$

This corresponds to an efficiency of converting mass into electromagnetic energy of

$$\eta_{eff} = 10^{-8} - 10^{-9}$$

Standard Accretion Theory

From the bolometric luminosity of $L \approx 2.1 \times 10^{36} erg/s$

one obtains an efficiency of $\eta_{eff} = \frac{L_{bol}}{\dot{M}_{Edd} c^2} \approx 5 \times 10^{-6}$

For the estimated accretion rate this would imply a much larger bolometric luminosity than actually observed:

$$L \approx 0.1 \times \dot{M}_{Edd} c^2 \approx 4 \times 10^{43} erg/s$$

This is larger by a factor of about 10^7

SgrA* is either very ineffciently accreting matter of very little of the matter available for accretion actually reaches the MBH, while the rest is blown away.

Dynamical Model for Accretion

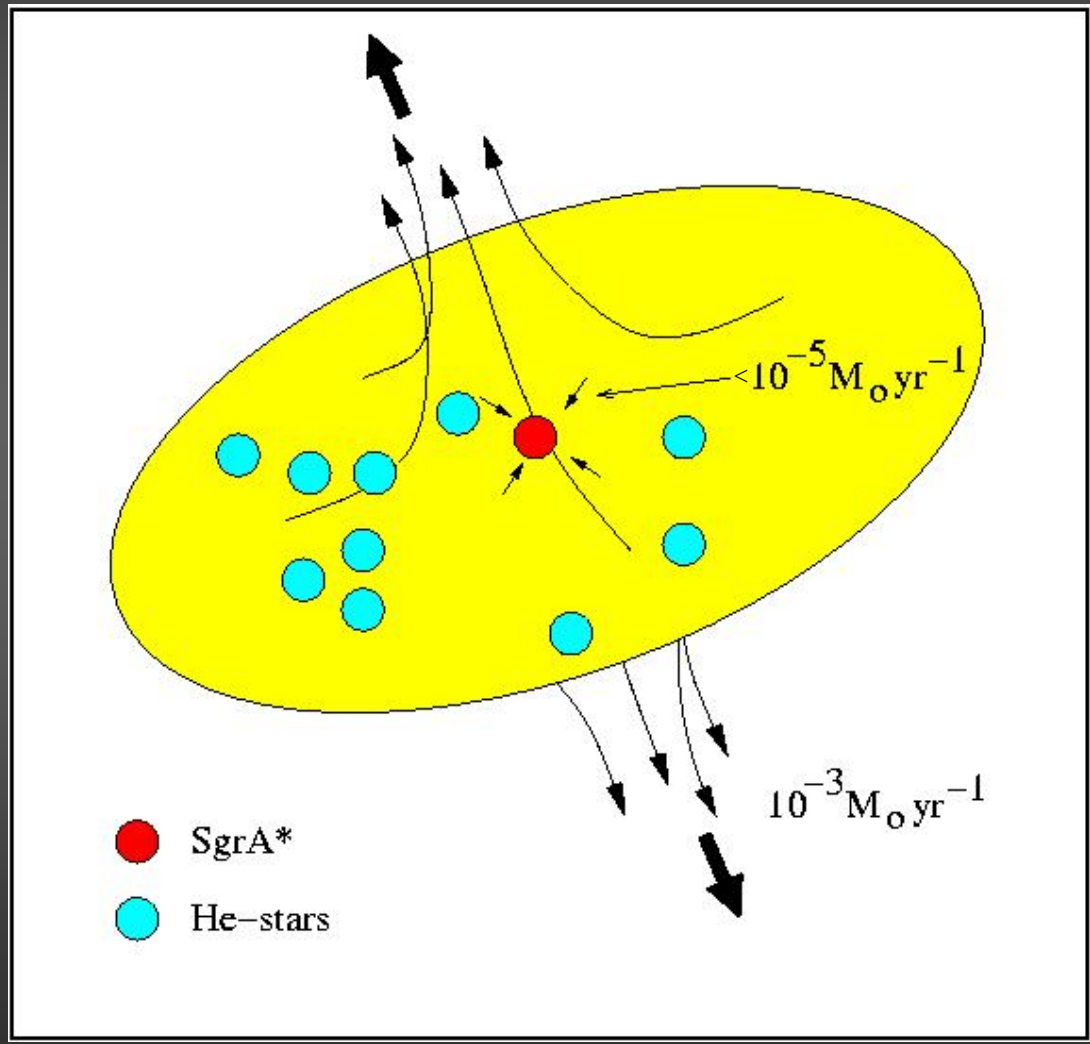
Ineraction between the ‘starburst’ and the black hole

Massloss from stars $10^{-3} M_o yr^{-1}$

radiation efficiency
of SgrA* $\approx 10^{-8}$

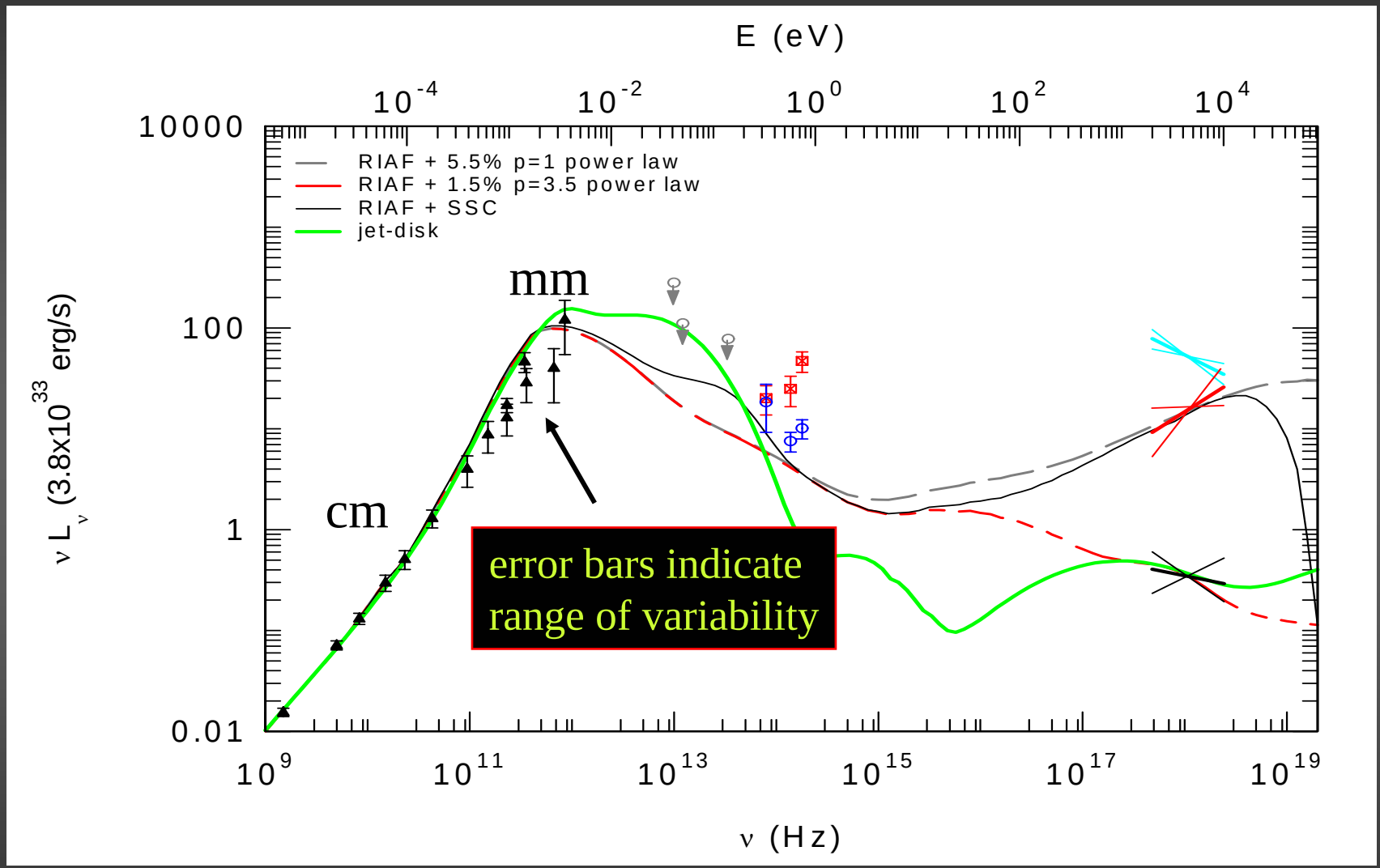
Bower et al. 2003:
RM of linear polarized
flux rules out large
accretion rates

Quataert 2003:
hydrodynamic calculations show
that almost the entire mass gets
blown away in a central wind.
Available for accretion: $10^{-5} M_o yr^{-1}$



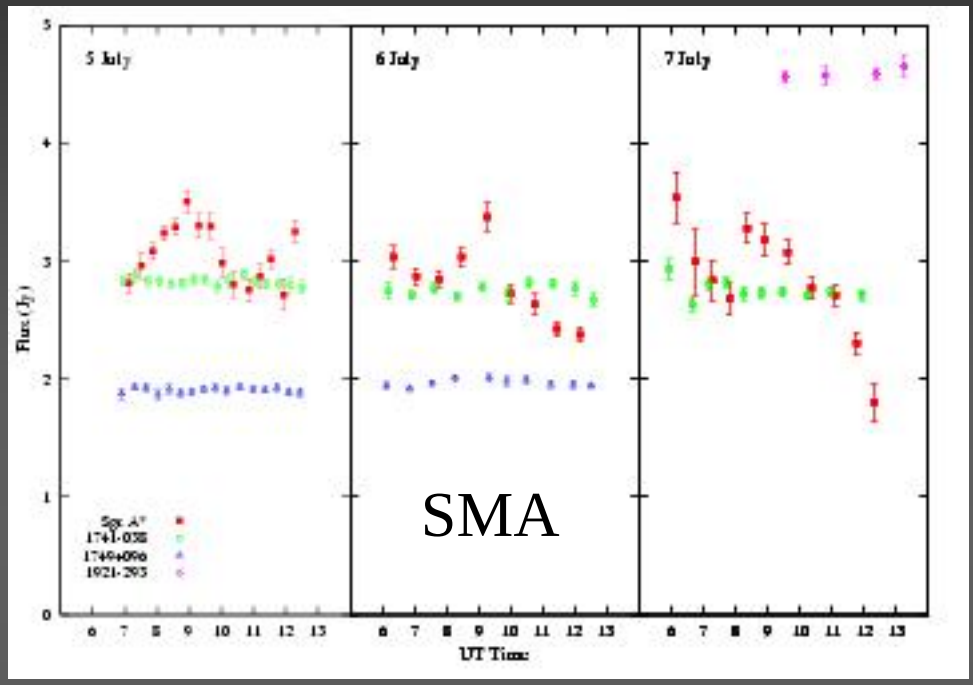
Radio Variability

Radio Variability



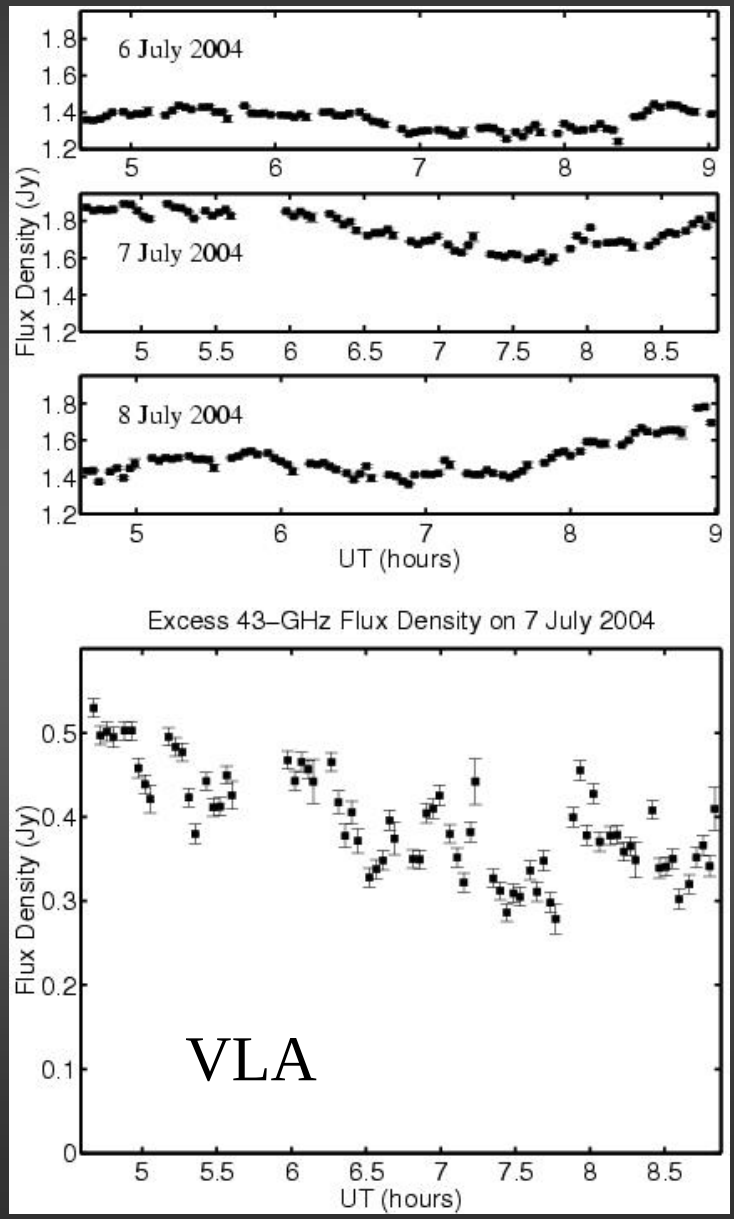
Radio: Zhao, Falcke, Bower, Aitken, et al. 1999-2003
X-ray: Baganoff et al. 2001, 2003, Goldwurm et al. 2003, Porquet et al. 2003,
NIR: Genzel et al. 2003, Ghez et al. 2003
models: Markoff, Falcke, Liu, Melia, Narayan, Quataert, Yuan et al. 1999-2001

mm/sub-mm Monitoring in 2004

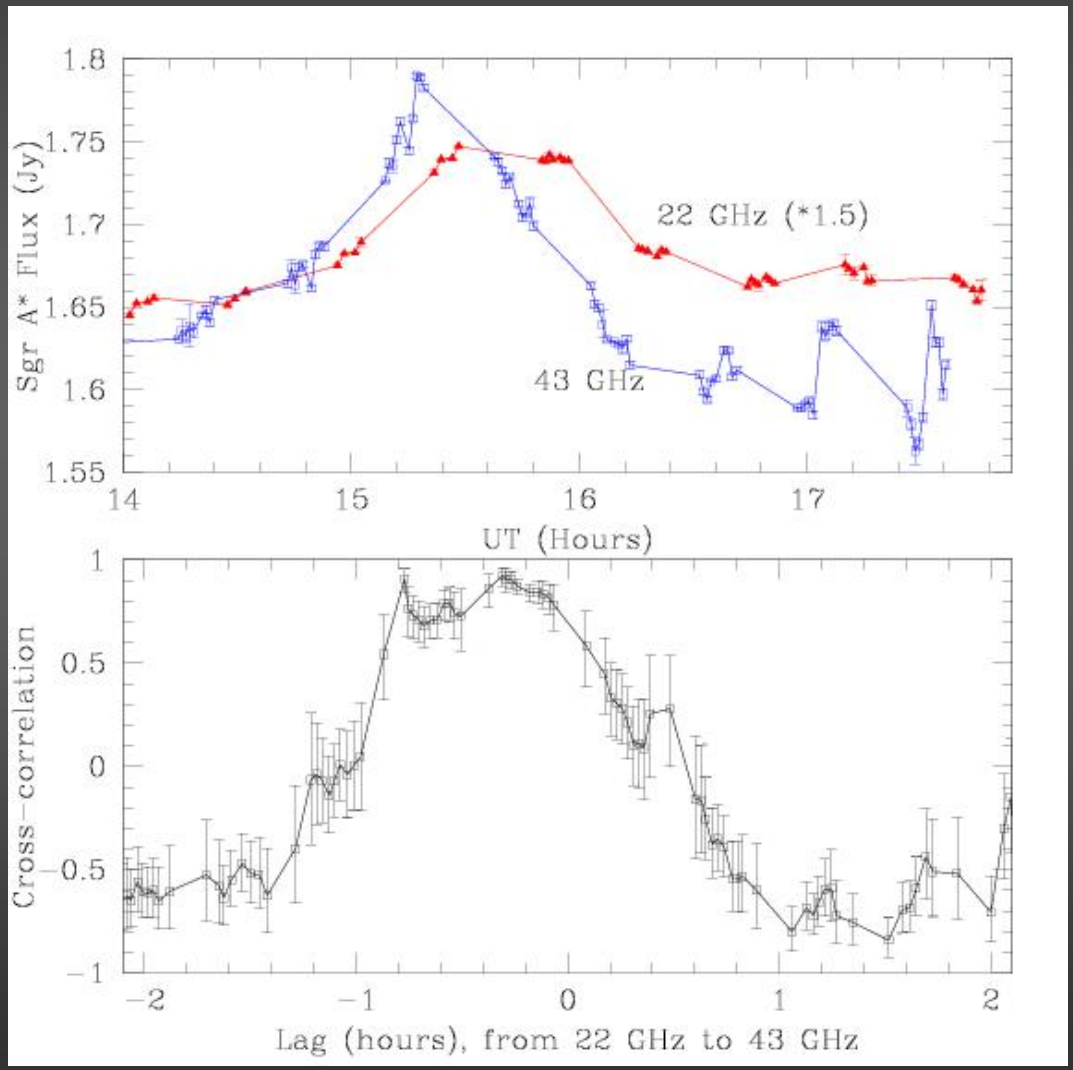


Eckart, Morris, Baganoff,
Bower, Marone et al. 2006 A&A in press

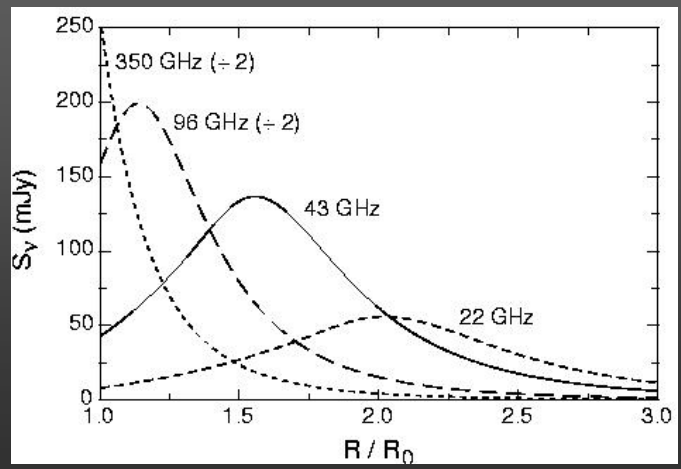
Indication for decaying flux density at 0.7 and 7 mm follwing an X-ray flare – consistent with adiabatic expansion



Adiabatic Expansion



Yusef-Zadeh et al. 2006, Astro-ph/0603685 submitted to ApJ

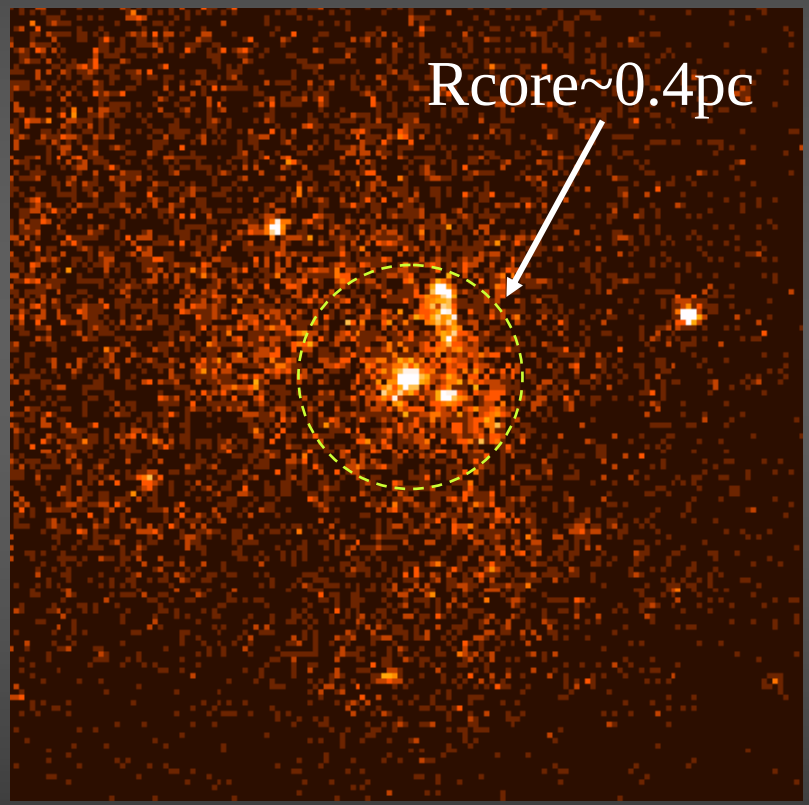


X-Ray/NIR Variability

Chandras Image of the Galactic Center

N

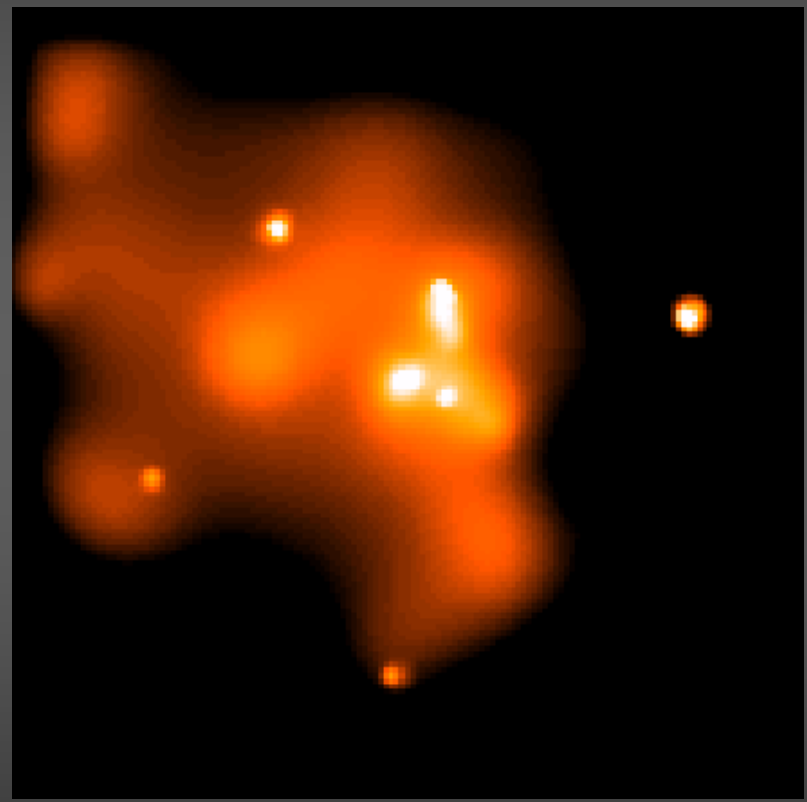
E



75“/10 lyr

0.5“ resolution

0.5-10 keV

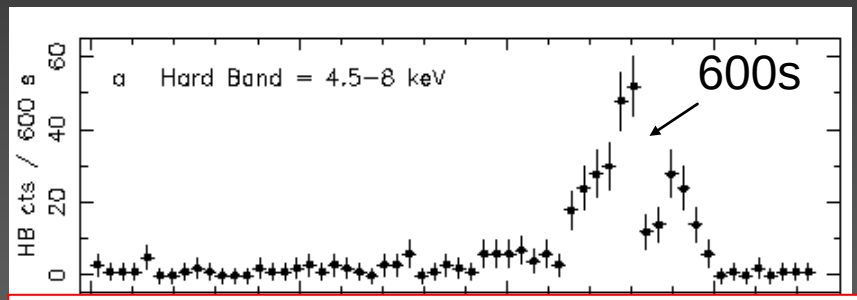


smoothed

Baganoff et al. Nature 2001

SgrA* burst in October 2000 in the 2-8 keV band

Baganoff et al. 2001, Nature 413, 45



$$R_{S,3\times10^6 M_o} = 9\times10^{11} cm$$

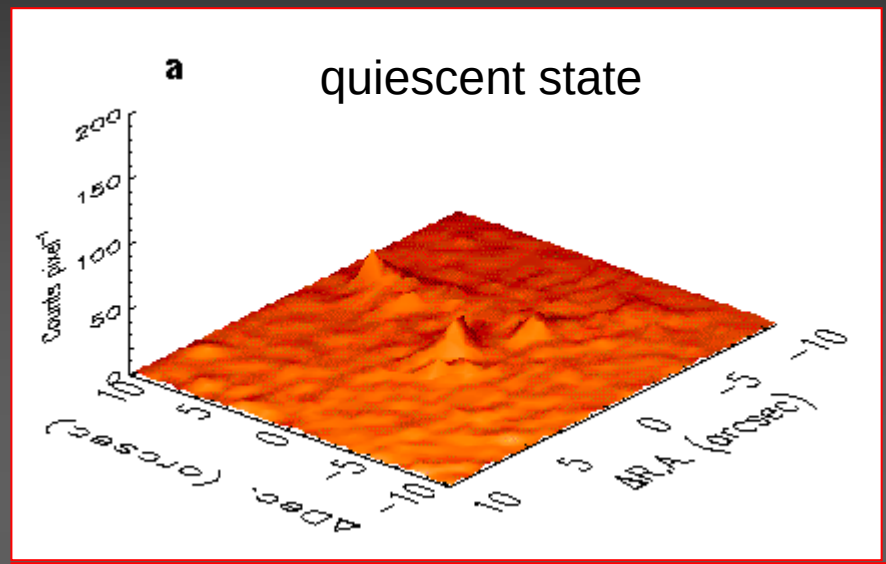
$$2.8h \approx 350R_S$$

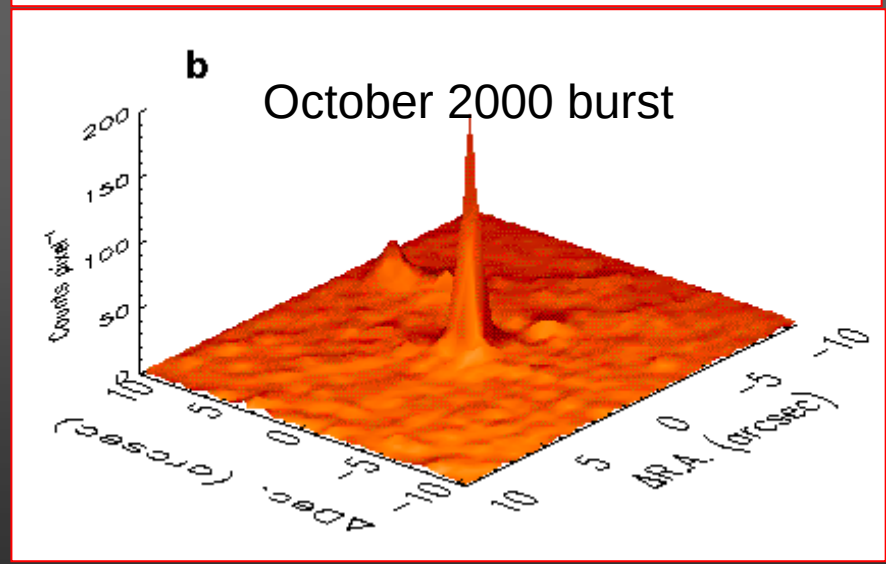
$$600s \approx 21R_S$$

$$S_{burst} \approx 50 \times S_{quiescent}$$

May 2002 *Monitoring*:

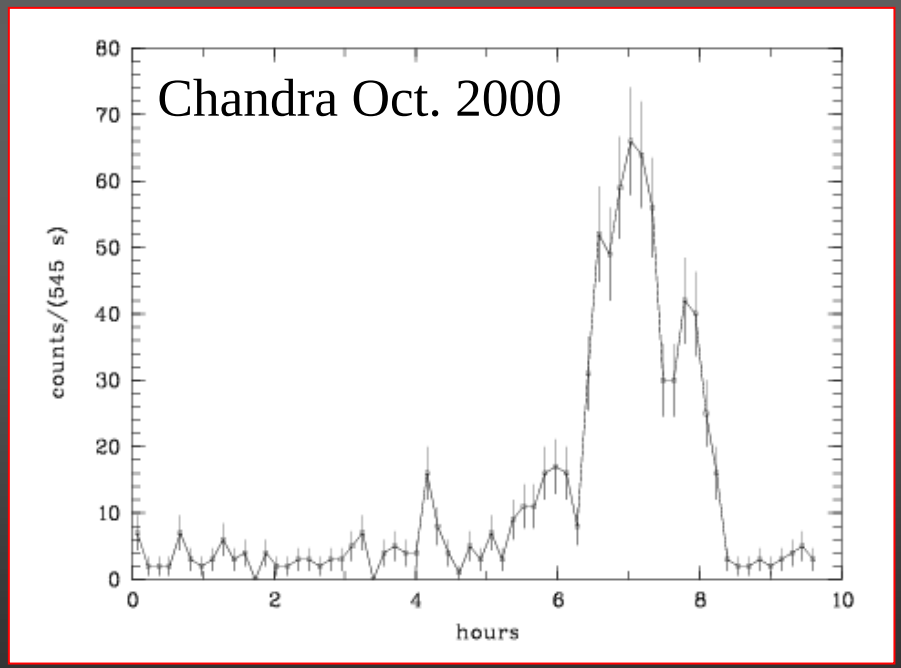
$$1.2 \pm 0.4 \ \ flares/day$$



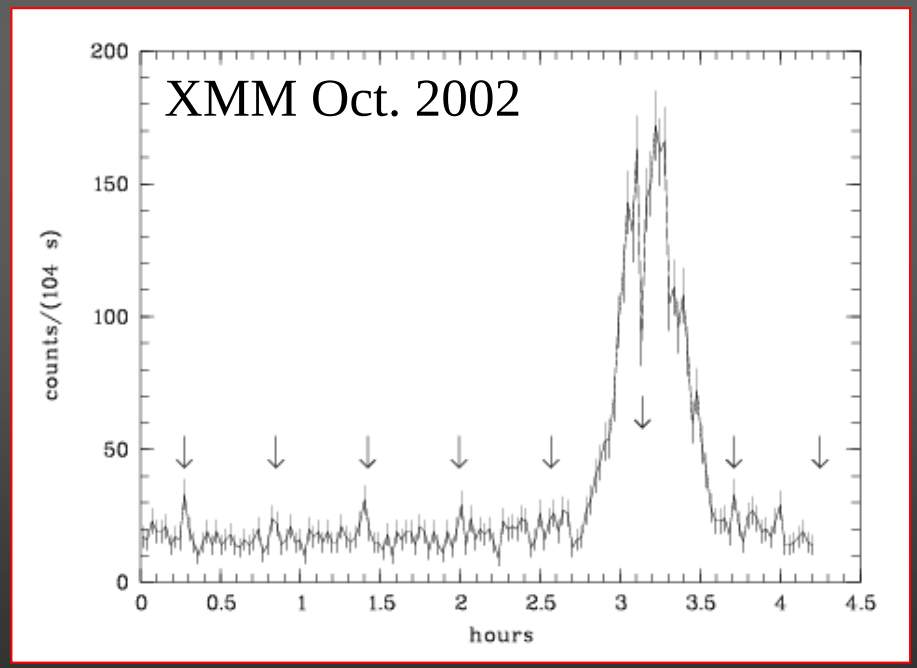


Detection of Cyclic Accretion Disk Modes ?

Analysing the two strongest X-ray bursts Aschenbach et al. 2004 (astro-ph/0401589) report the detection of cyclic modes associated with accretion disks.

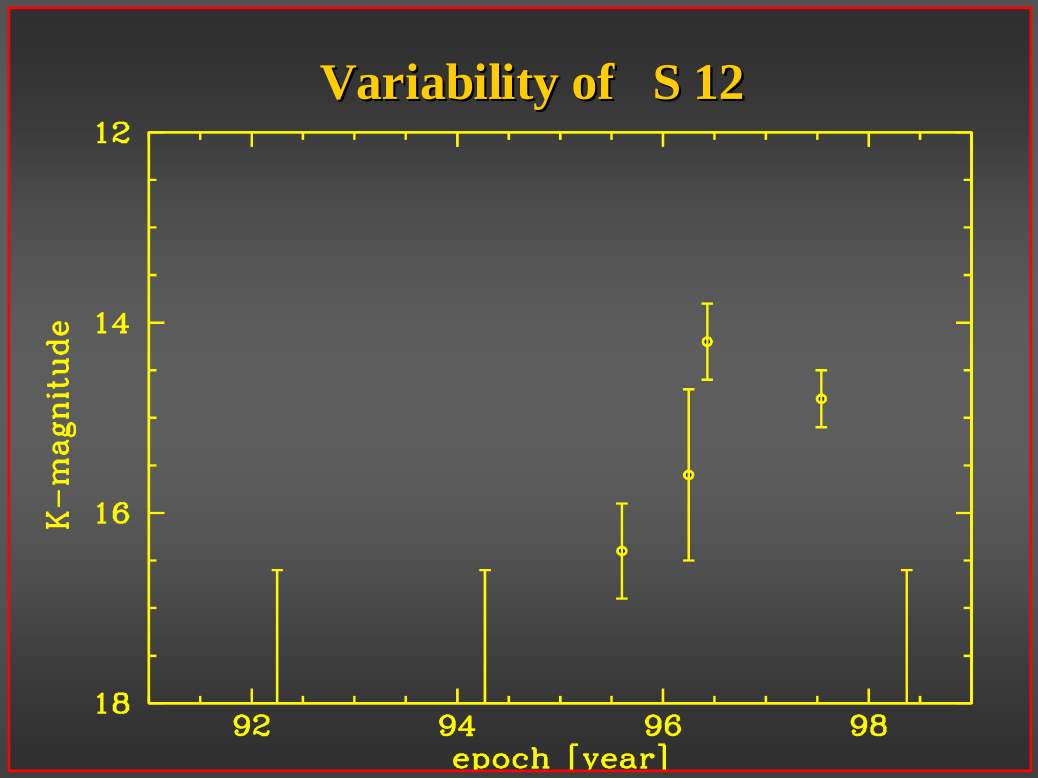


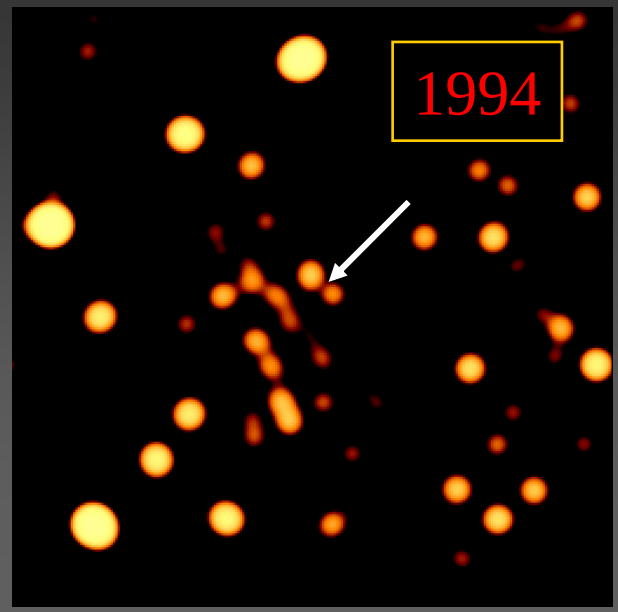
Baganoff et al. 2001

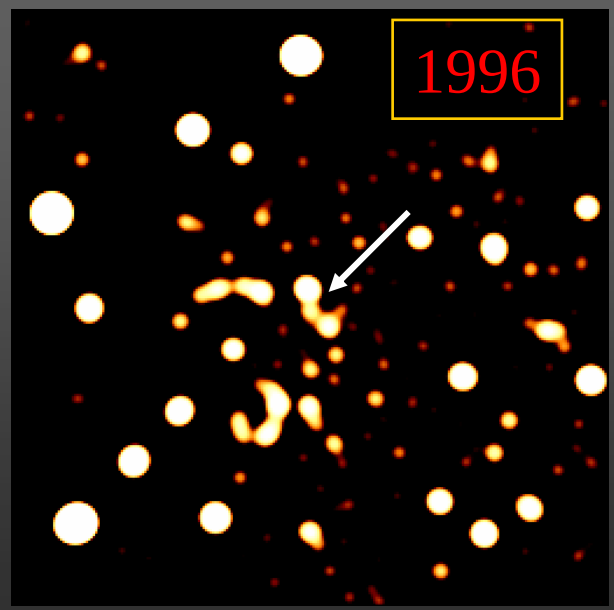


Porquet et al. 2003

Why is SgrA* so faint?



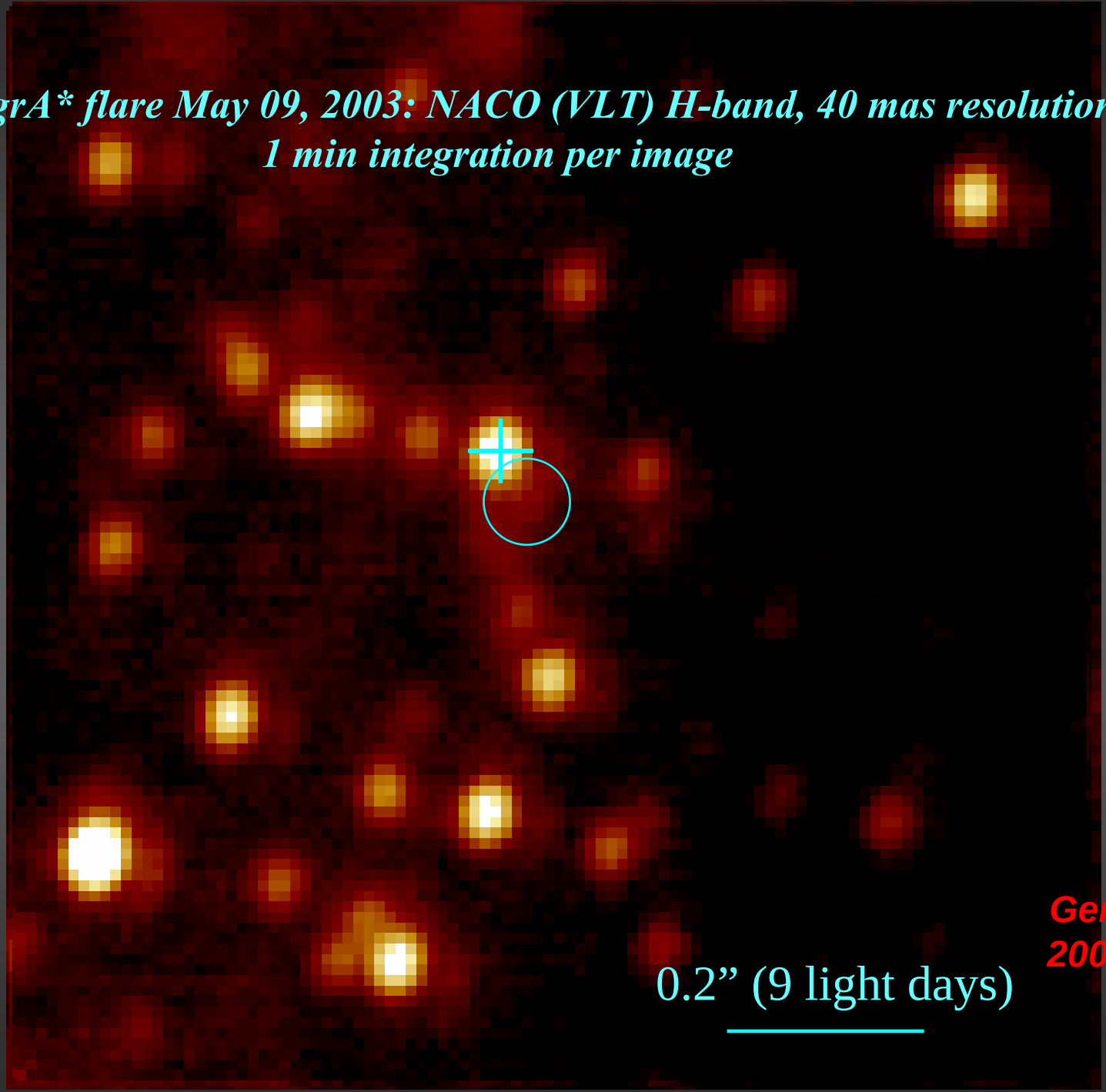




Genzel et al. 1997, MNRAS 291, 219

Narayan et al. 1998, Ap.J. 492, 554

SgrA flare May 09, 2003: NACO (VLT) H-band, 40 mas resolution, 1 min integration per image*



Genzel et al. 2003, Nature

X-Ray/NIR/Radio Correlations

SgrA*

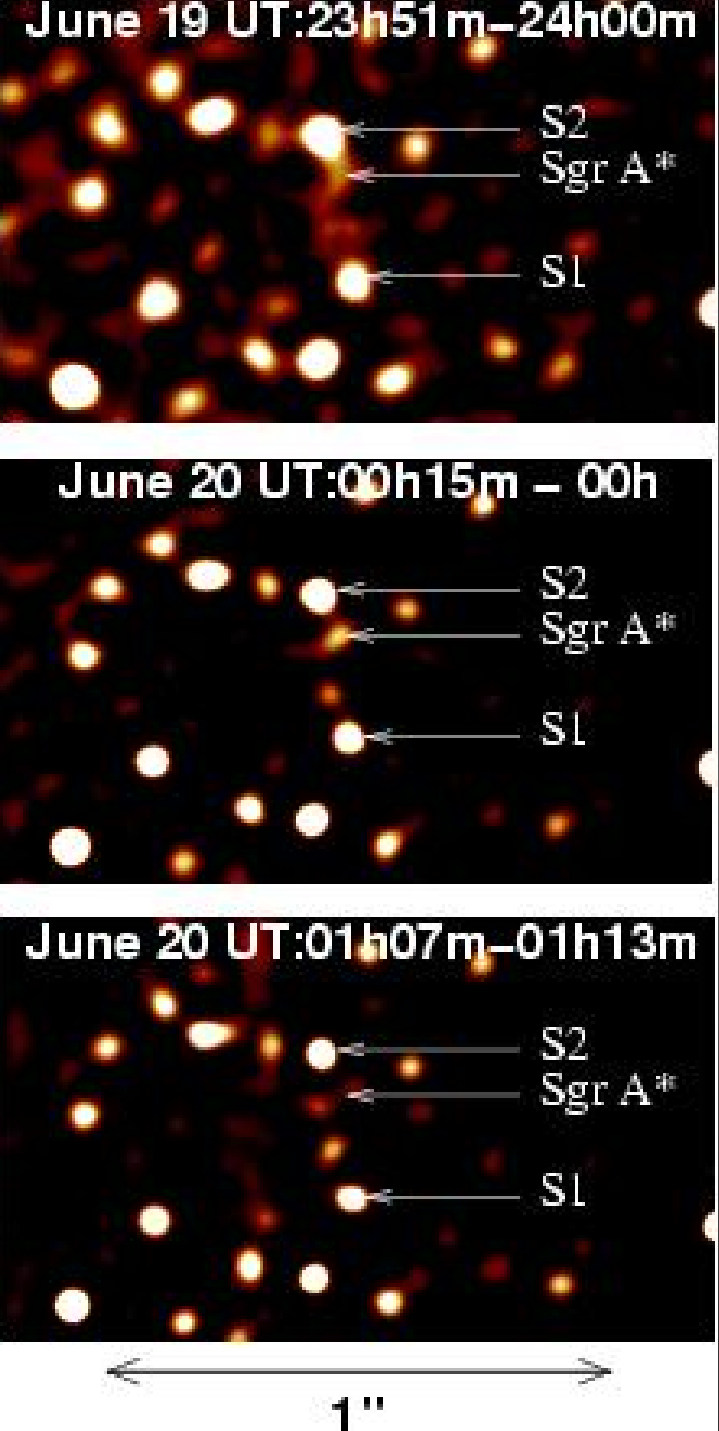
What is the Emission Mechanism?

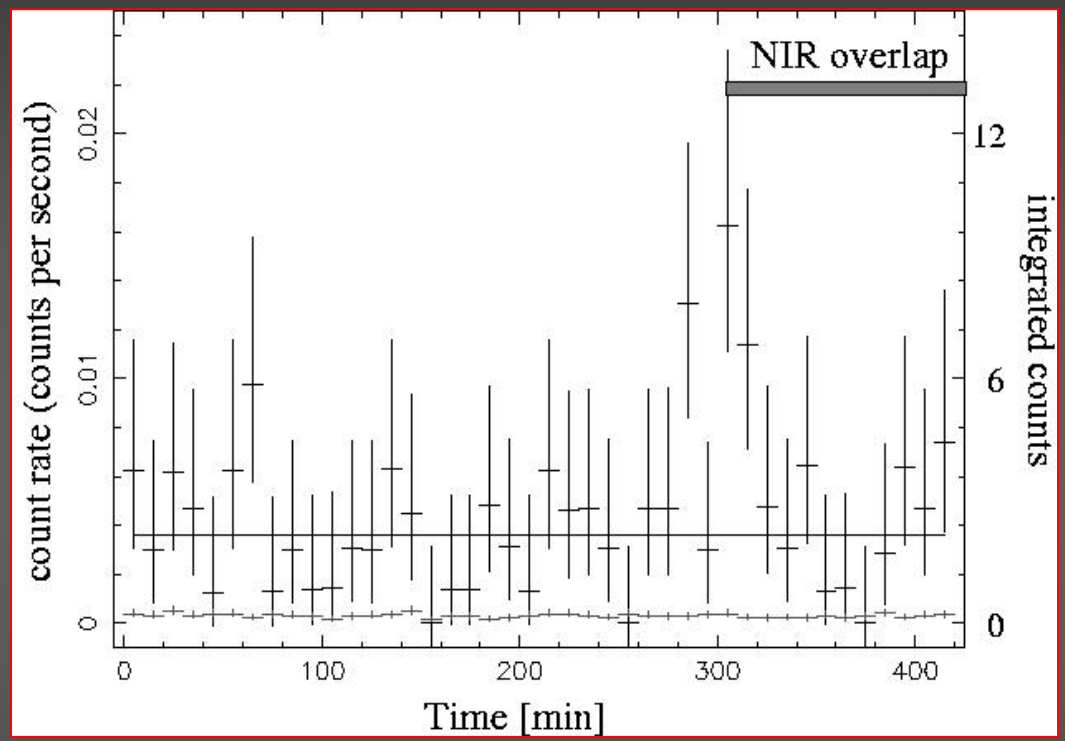
What is the Nature of the Dark Mass Concentration at the Center of the Milky Way?

*Simultaneous NIR / X-ray Measurements of Sgr A**

2003

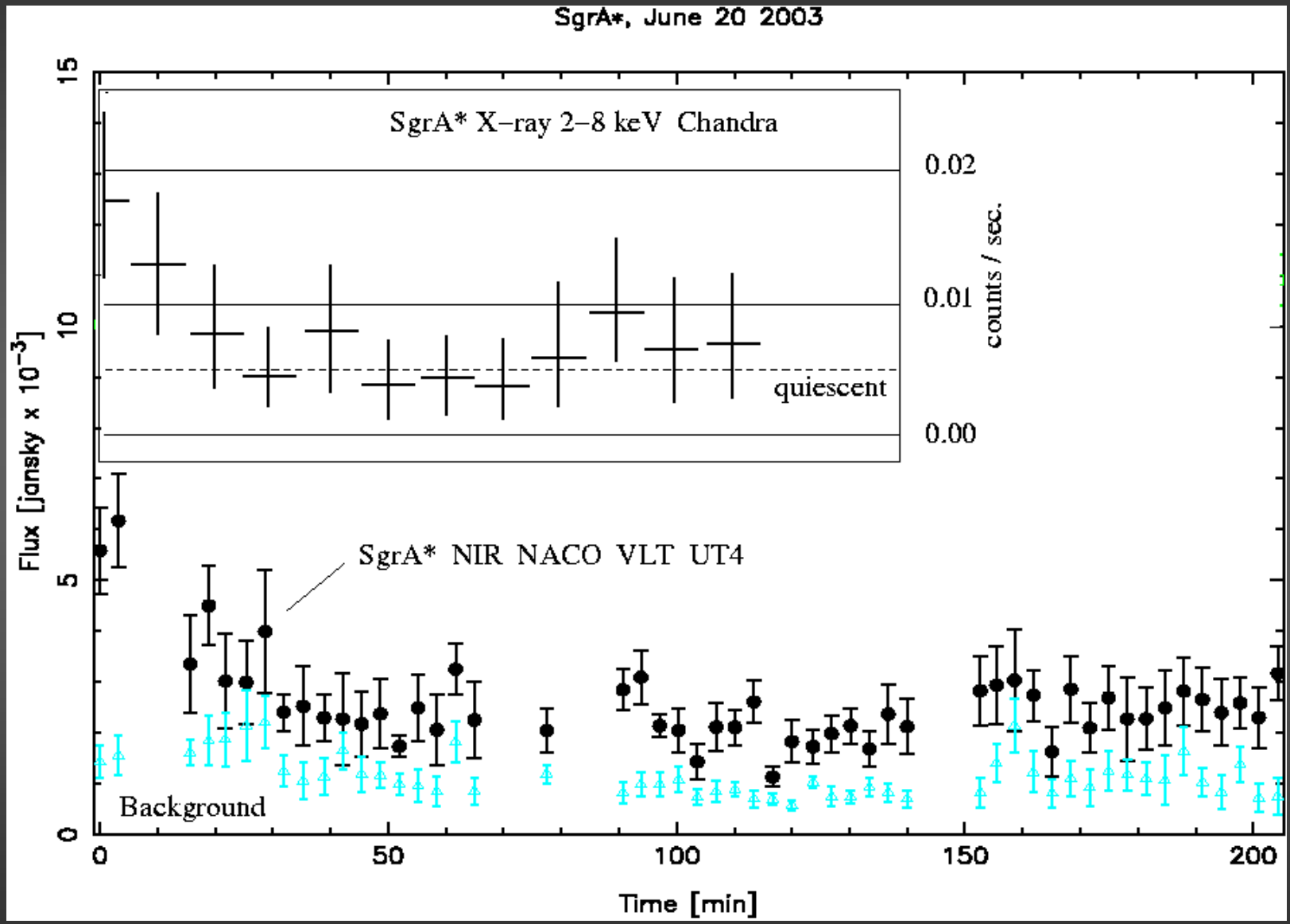
Simultaneous NIR/X-ray Observations





Eckart, Baganoff, Morris, Bautz, Brandt, Garmire, Genzel, Ott, Ricker, Straubmeier, Viehmann, Schödel, Bower, and Goldston 2004 A&A 427, 1

SgrA*: First Simultaneous K-band/X-ray Observations



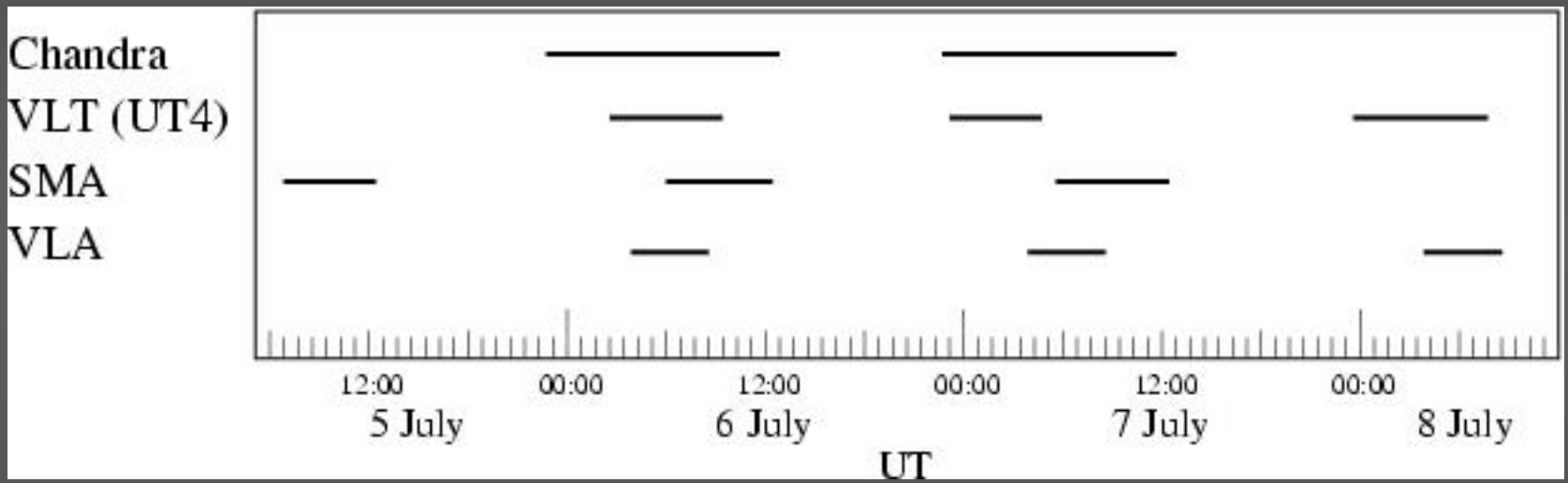
Eckart et al. 2004

NACO/VLT June 20, 2003

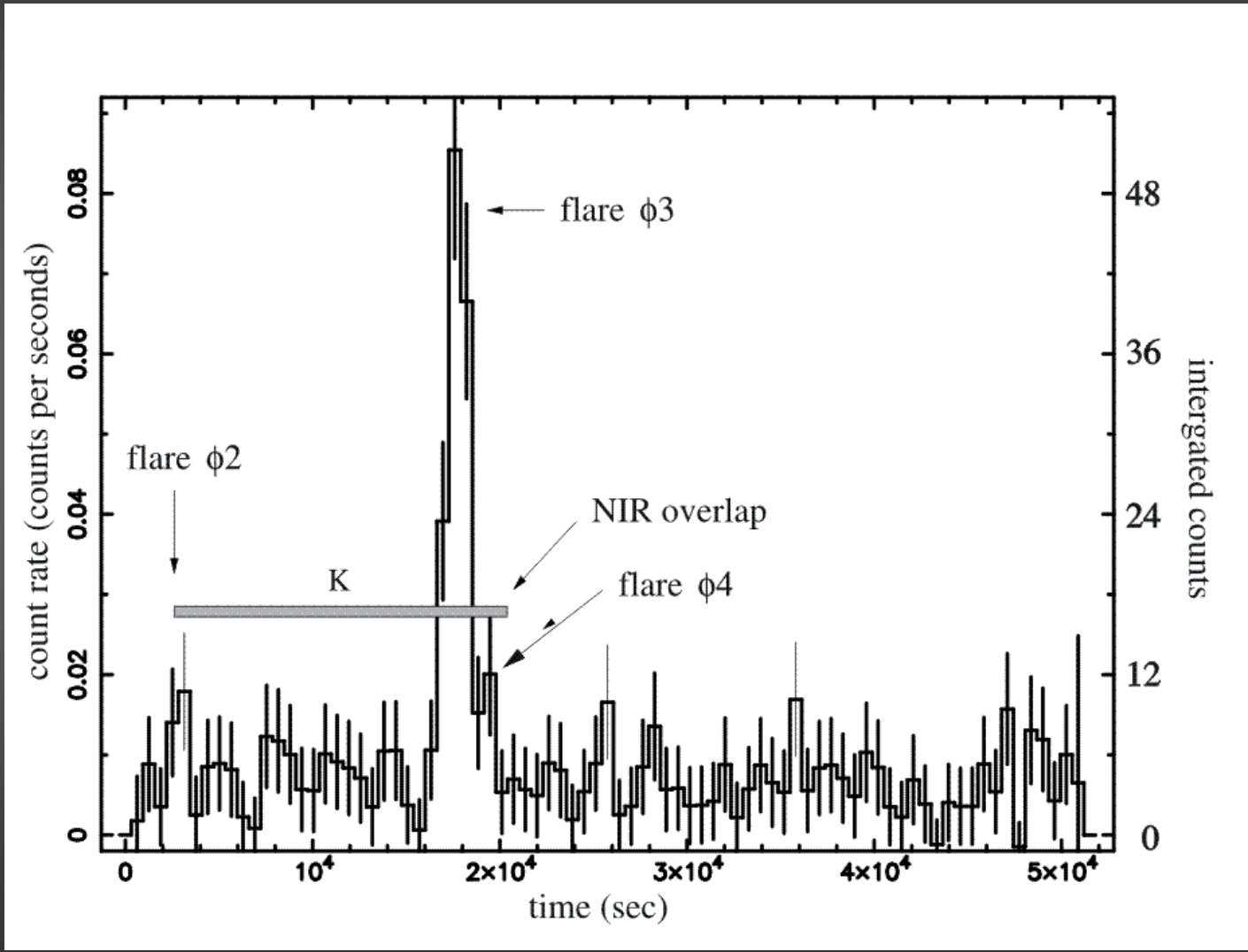
*Simultaneous NIR / X-ray Measurements of Sgr A**

2004

mm/sub-mm Monitoring in 2004



SgrA*: Simultaneous NIR/X-ray Observations



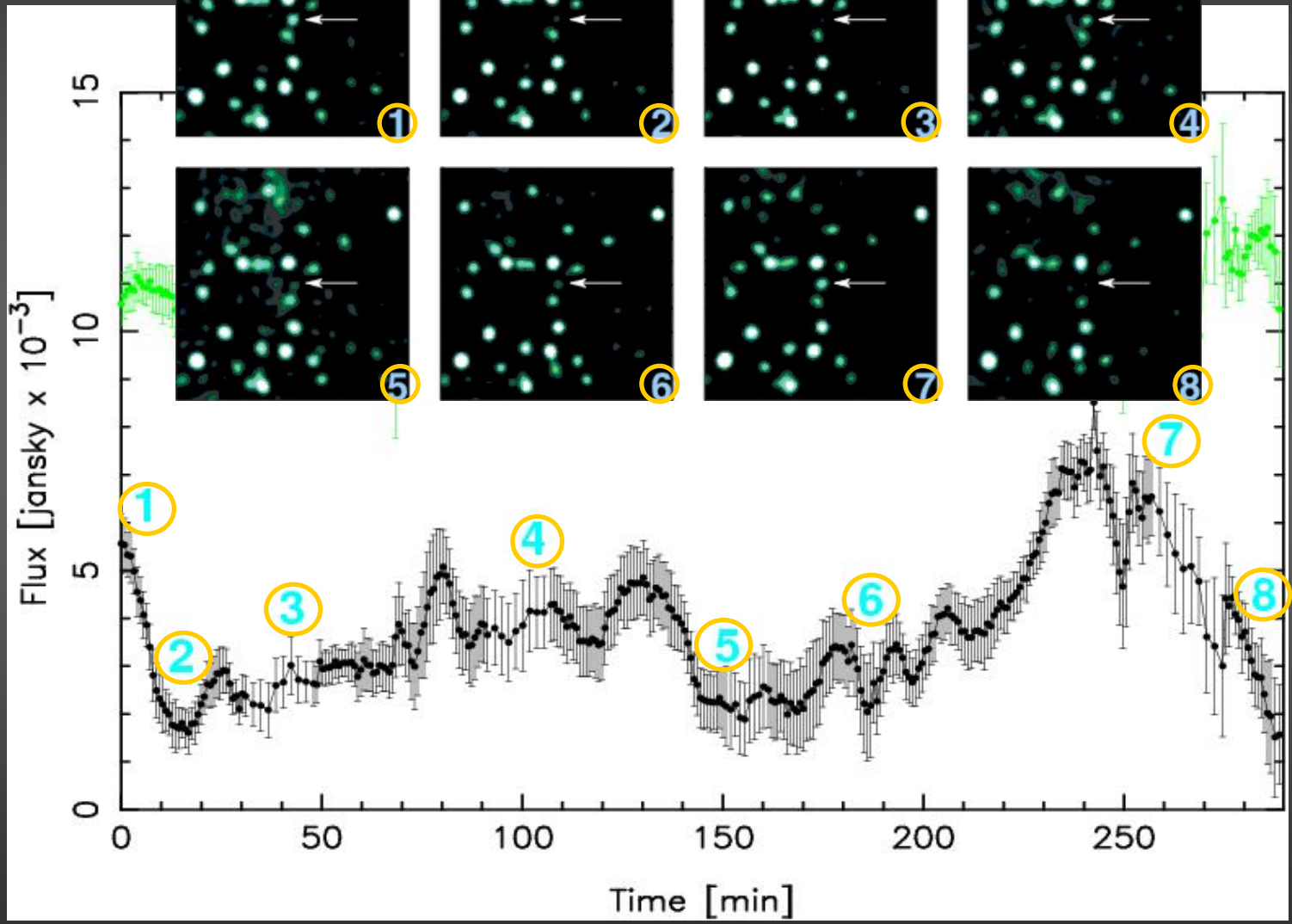
CHANDRA, 7 July 2004

Eckart et al. 2006, A&A in press

SgrA*: Simultaneous NIR/X-ray Observations

Comparison with imges demonstrates the variability shown in the lightcure.

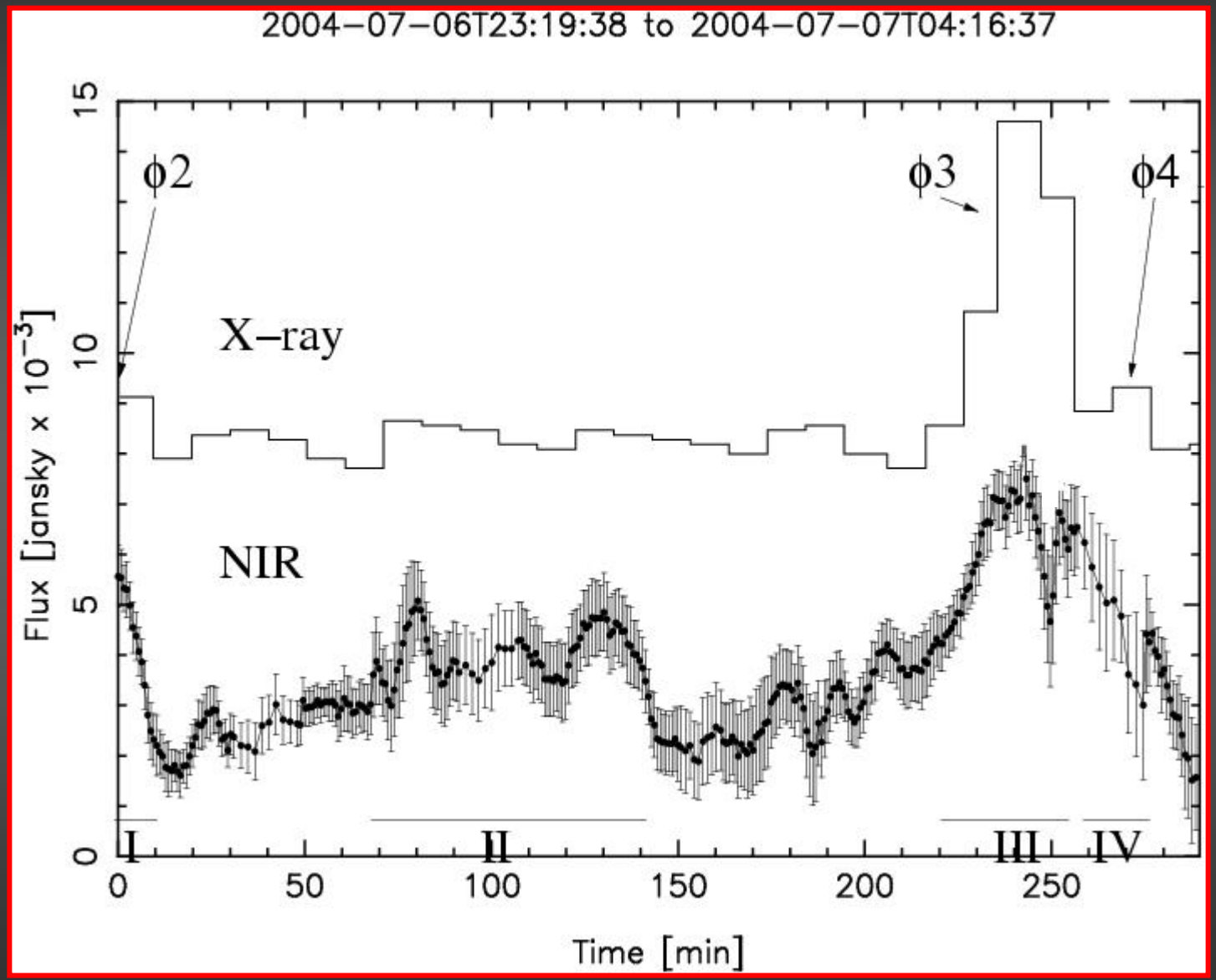
Flare emission originates to within <10mas form the position of SgrA*



NACO/VLT / July 2004

Eckart et al. 2006, A&A in press

Simultaneous Flare Emission

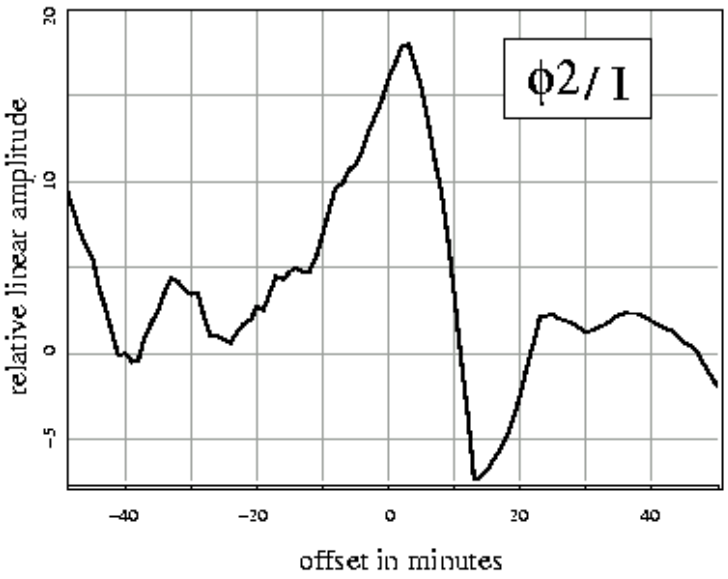


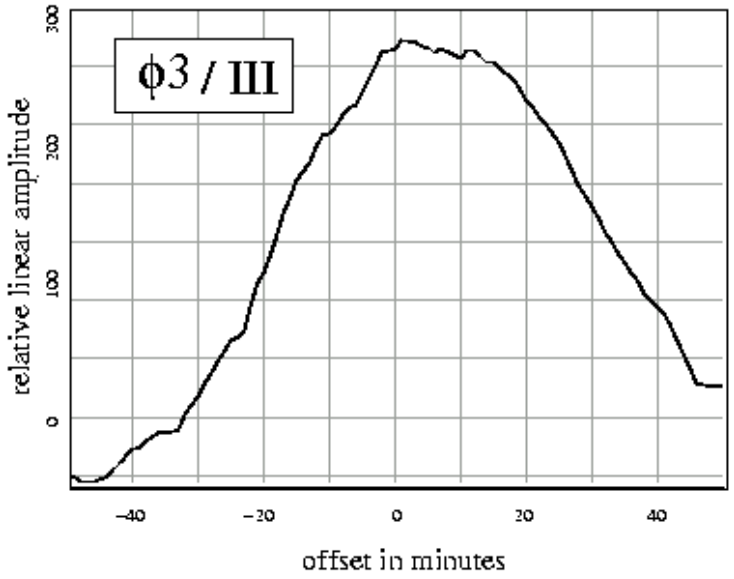
~225nJy

~6mJy

Flare emission originates to within <10mas form the position of SgrA*

Cross-Correlation of Simultaneous NIR/X-ray Flares

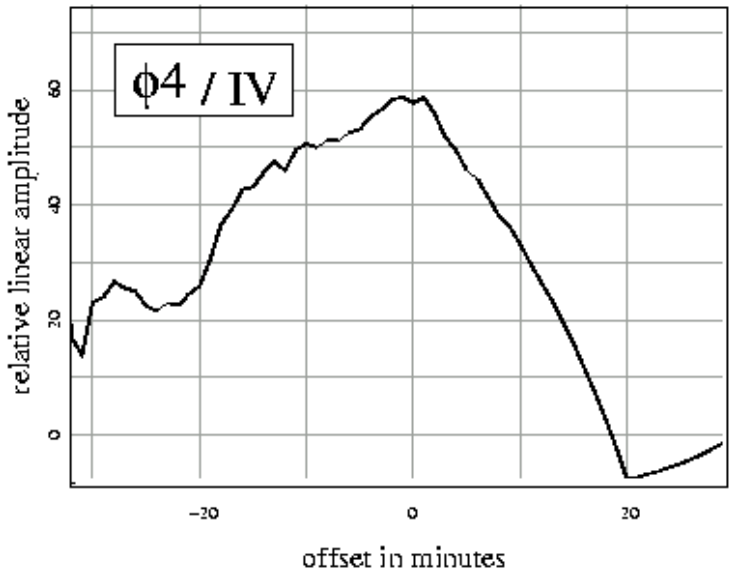




ϕ2/I and ϕ4/IV are dominated by a decaying flank; ϕ3/III is domainated by a rising flare flank.

Time lags are less <10-15 minutes

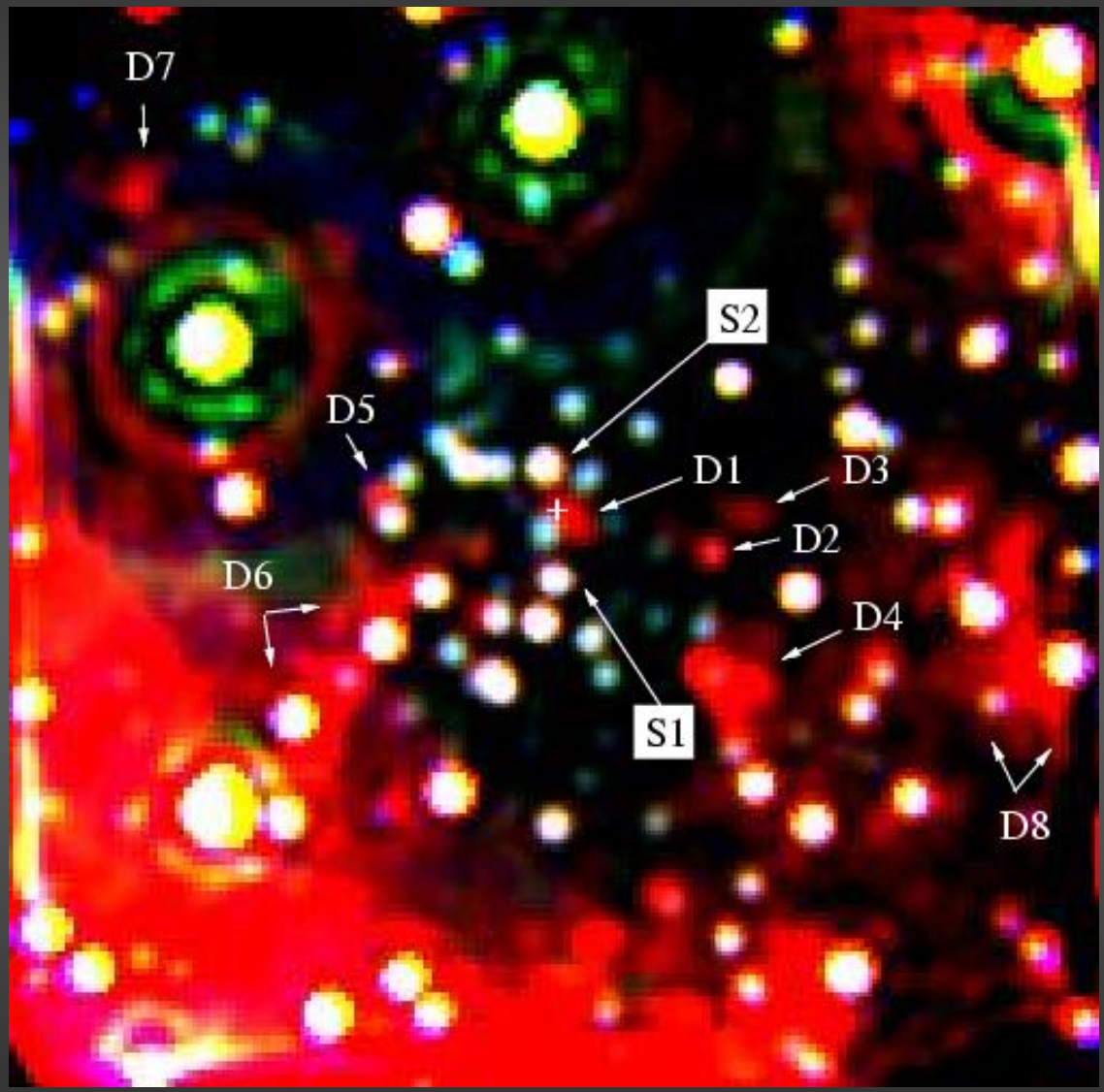
NIR and X-ray flares are well correlated.



IQ-state subtracted

NIR/MIR spectral energy distribution from the central arcsecond

Detection of a Dust Component along the Line of Sight towards SgrA*



5“x5“

HKL multi-color image of the central 2.6“x2.6“ taken with NACO. L-band is in red.

Fore-/Backgrond dust component 26mas west of SgrA*
~1000 AU at 8 kpc
(see also Ghez et al. 2004)

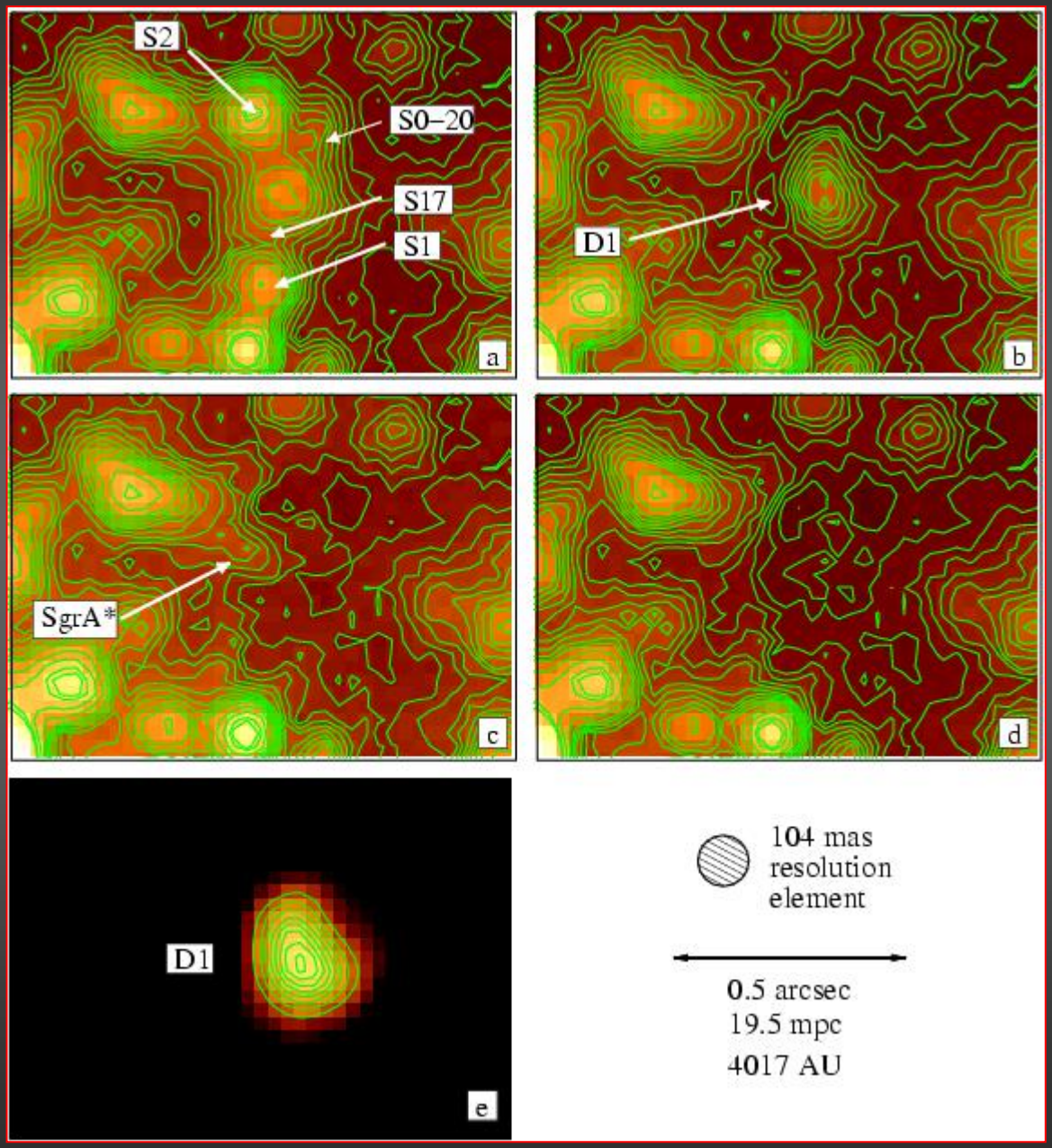
High angular resolution required in the MIR!!

Several of those dust blobs are seen across the field

all

D1

Detection of a Dust Component alongthe Line of Sight towards SgrA*



SgrA*

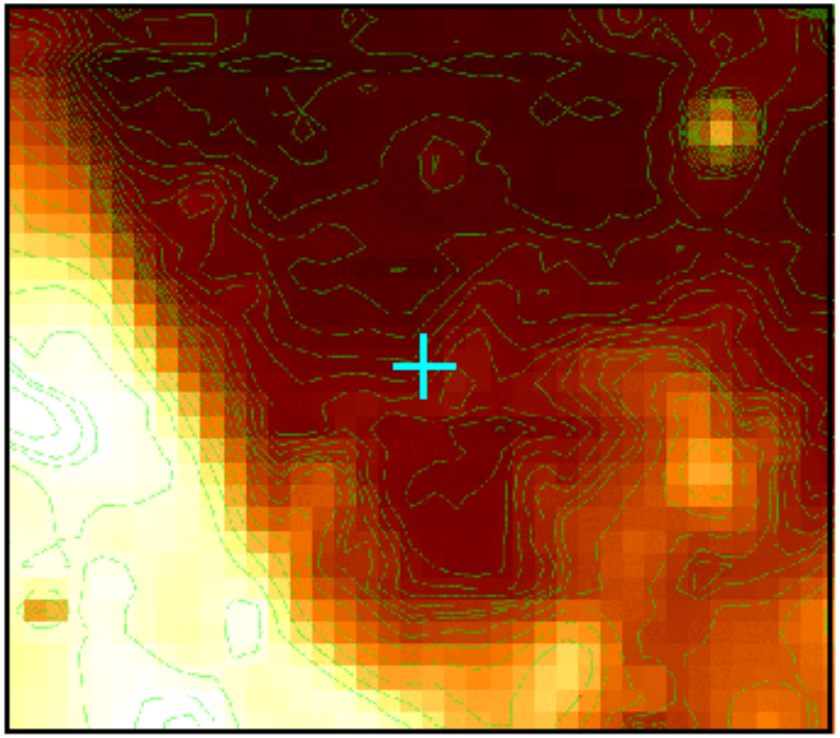
S1, S2, S17, S2-20 D1 and SgrA* subtracted

Eckart et al. 2006, A&A in press
see also Ghez et al. 2005

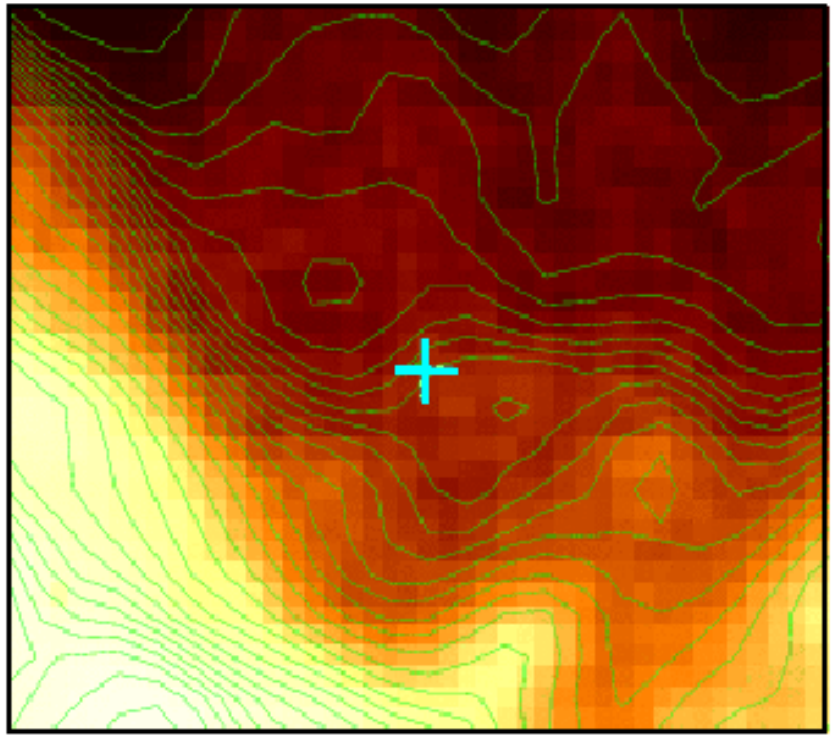
D1 only

The total L-band luminosity of the dust component D1 is almost as large as that of S2.

VISIR VLT Observations



8.6 μm



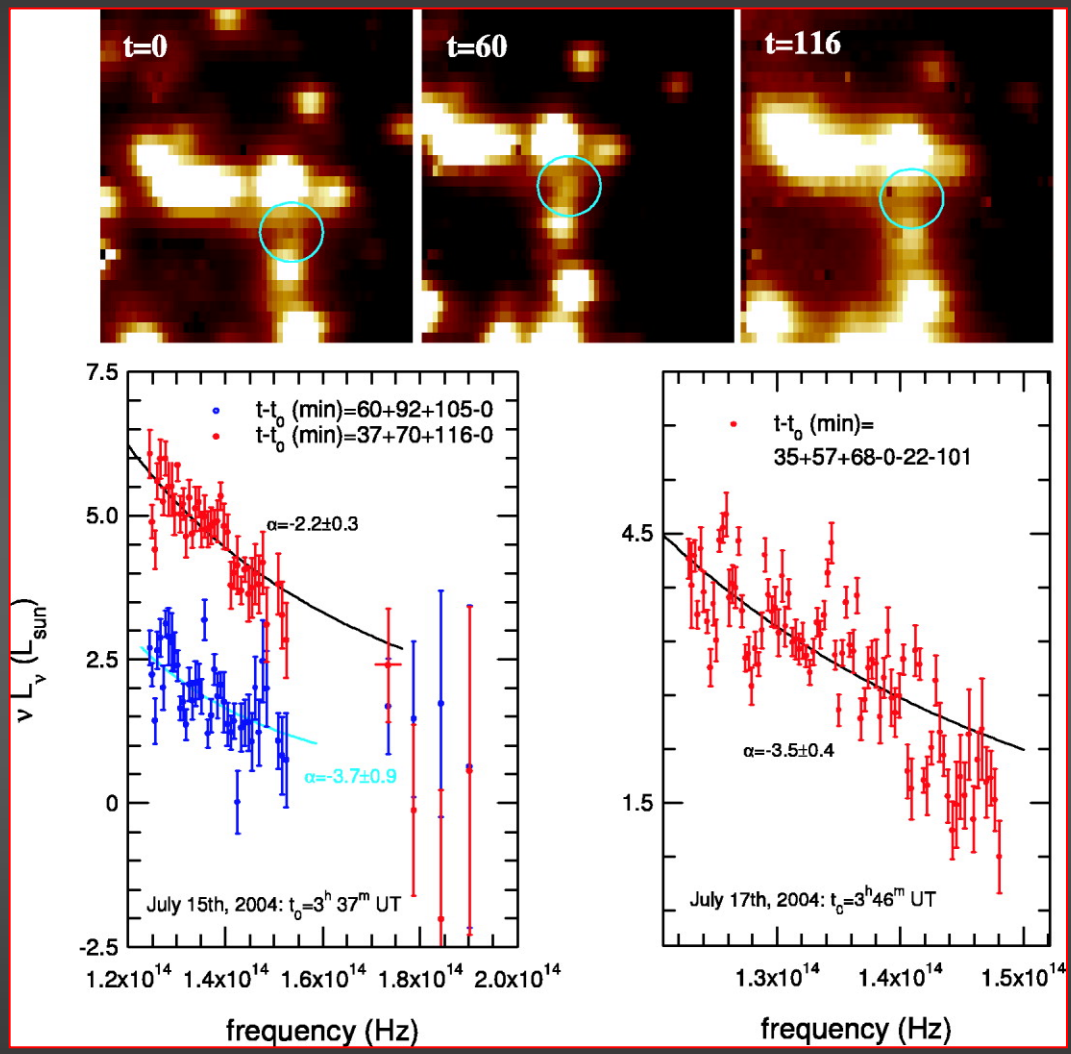
19.5 μm

field of view: 5.0“x4.4“
cross marks position of SgrA*

positional uncertainty +-0.2“
positioning via IRS3, 7, 21, 10W and in addition at 8.6 mm IRS 9, 6E, and 29

Eckart et al. 2006

Steep NIR Spectra of SgrA* Flares



Eisenhauer et al. 2005
see also
Gillessen et al. 2006

MIR Fluxes

3.8 μm 22+/-10 mJy

8.6 μm 50+/- 10 mJy

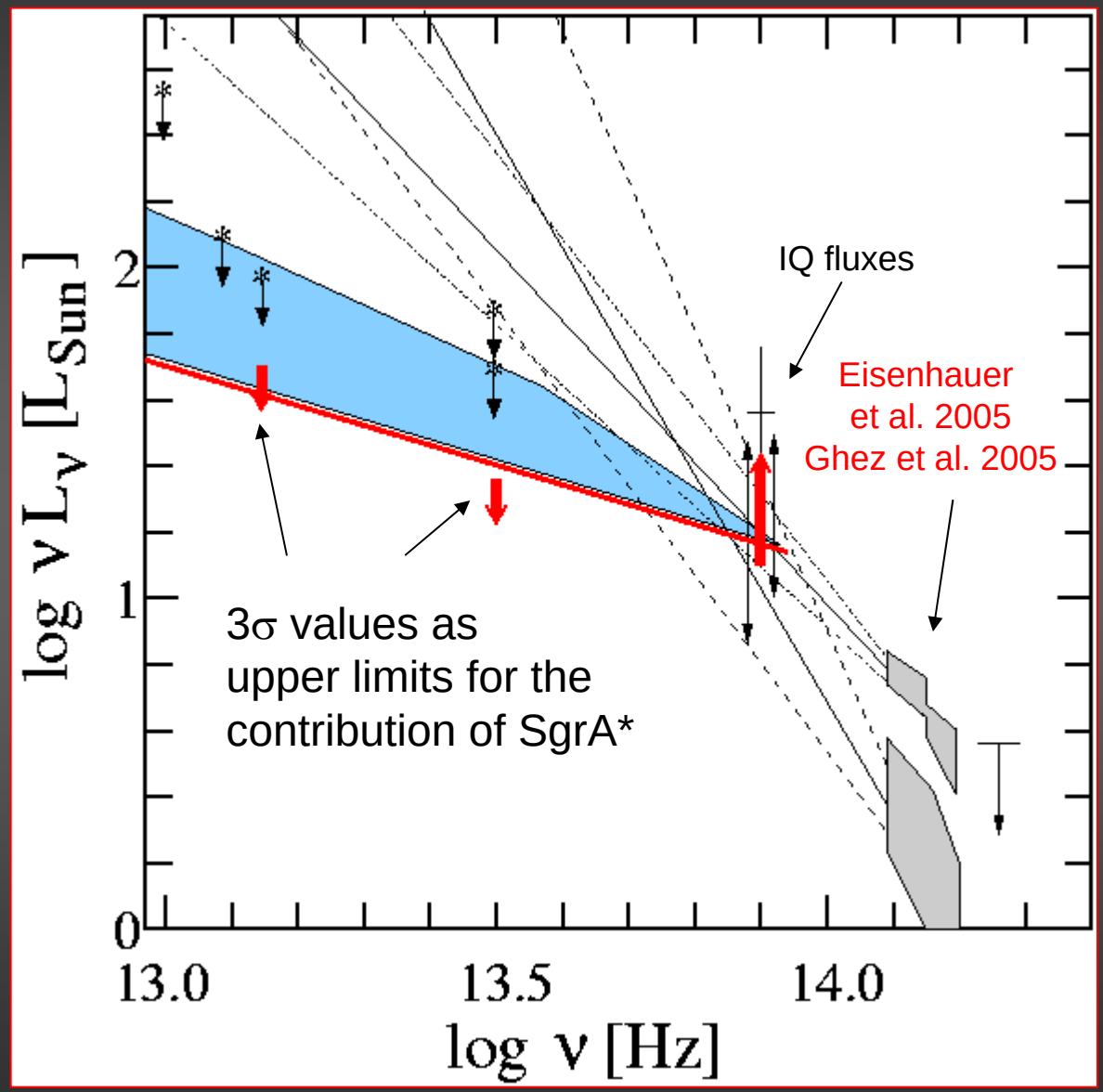
19.5 μm 320+/-80 mJy

The emission at 8.6μm and 19.5μm is dominated by dust

spiral ratio

$S_{3.8} \rightarrow S_{8.6}$

$S_{19.5} / S_{8.6}$ = spiral ratio

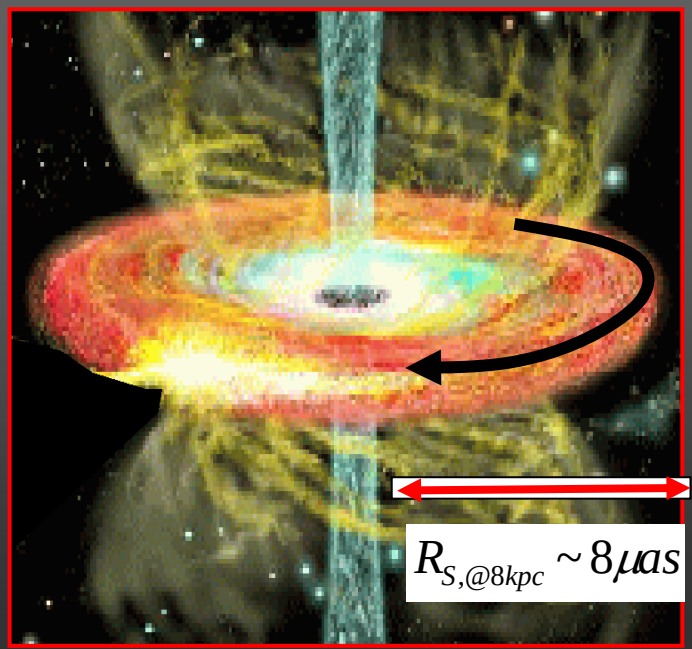


A simple SSC Model with a Synchrotron Spectrum Truncated in the MIR/NIR

Table of Exemplary Models

model 1D	S_{NIR} synchr. (mJy)	S_{NIR} SSC (mJy)	S_{X-ray} (nJy)	B (G)	$\nu_{max,pks}$ (GHz)	$S_{max,pks}$ (Jy)	size (μas)	$\alpha_{NIR/X-ray}$	c/ν_0 (μm)
IQ1	0.8	2.0	<18	17	820	3.9	7.9	1.3	-
IQ2	-	3.0	<27	5	820	7.7	8.1	1.3	-
IQ3	(25)1	0.1	<17	80	1000	16.0	17.5	1.0	15
IQ4	2.0	0.02	<15	38	1500	0.33	1.5	0.8	-
F1	(18)6	1.13	65	68	1640	11.5	8.5	1.1	5
F2	(300)6	0.1	230	100	1640	5.7	8.5	0.4	90

$$\gamma_e = (1-\beta_e^2)^{-1/2}$$
$$\Gamma_{bulk} = (1-\beta_{bulk}^2)^{-1/2}$$
$$\delta = \Gamma^{-1}(1-\beta_{bulk}\cos\phi)^{-1}$$

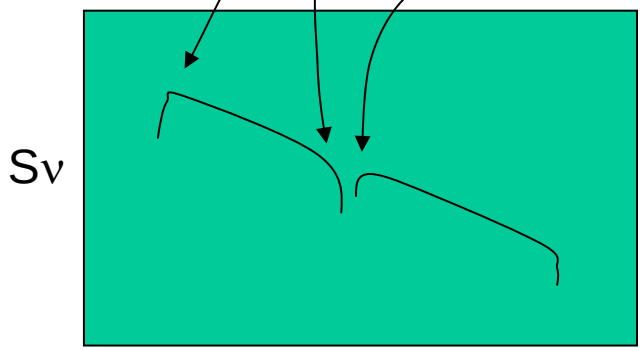


SSC model

ν_m at ~1 THz

MIR/NIR synchr. cutoff

ν_2 at or below NIR



$\gamma_e \sim 10^3$

$\Gamma = 1.2 - 2.0$

$\delta = 1.3 - 2.0$

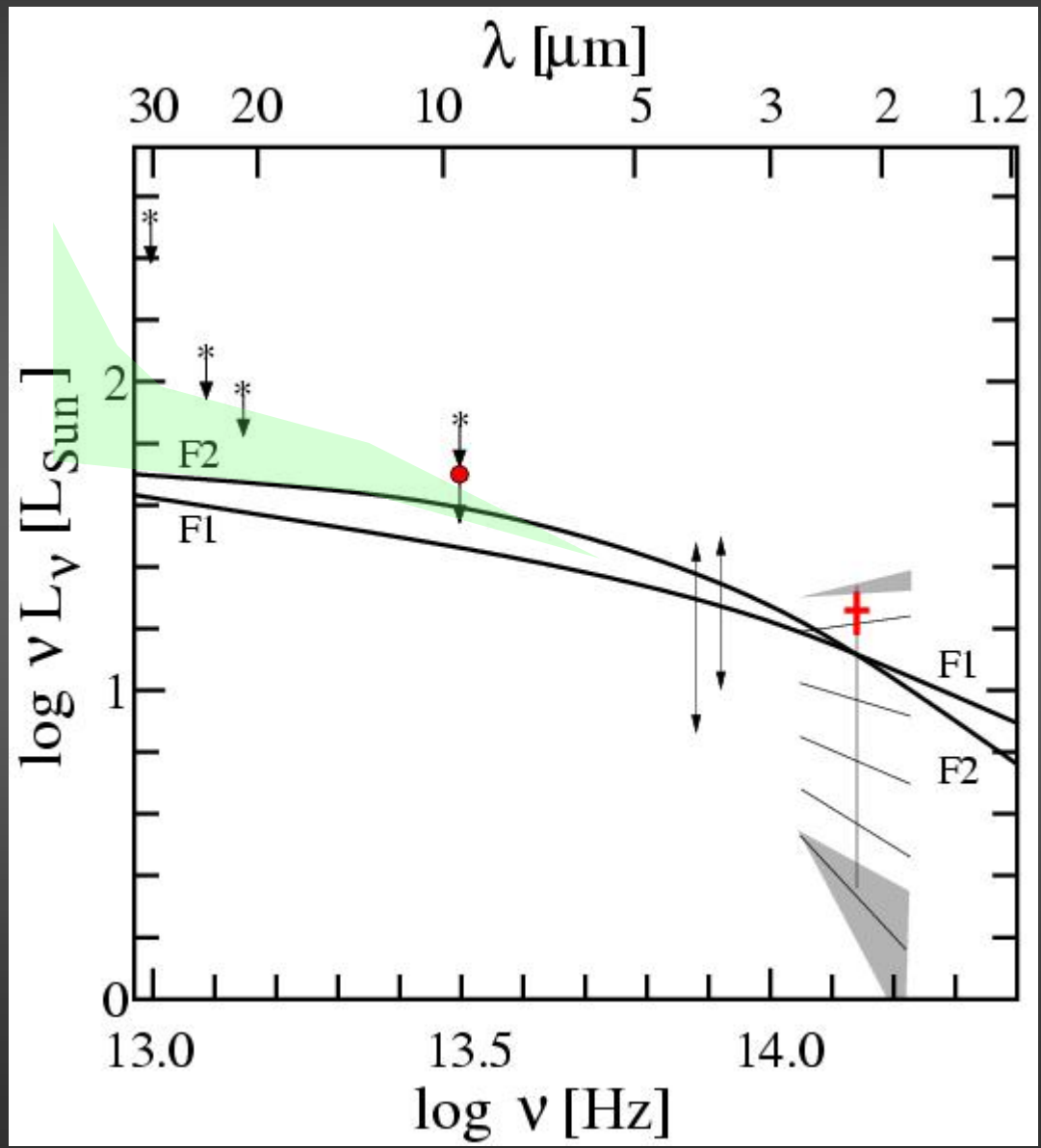
$(\phi = 10^o - 45^o)$

Simultaneous weak flare models

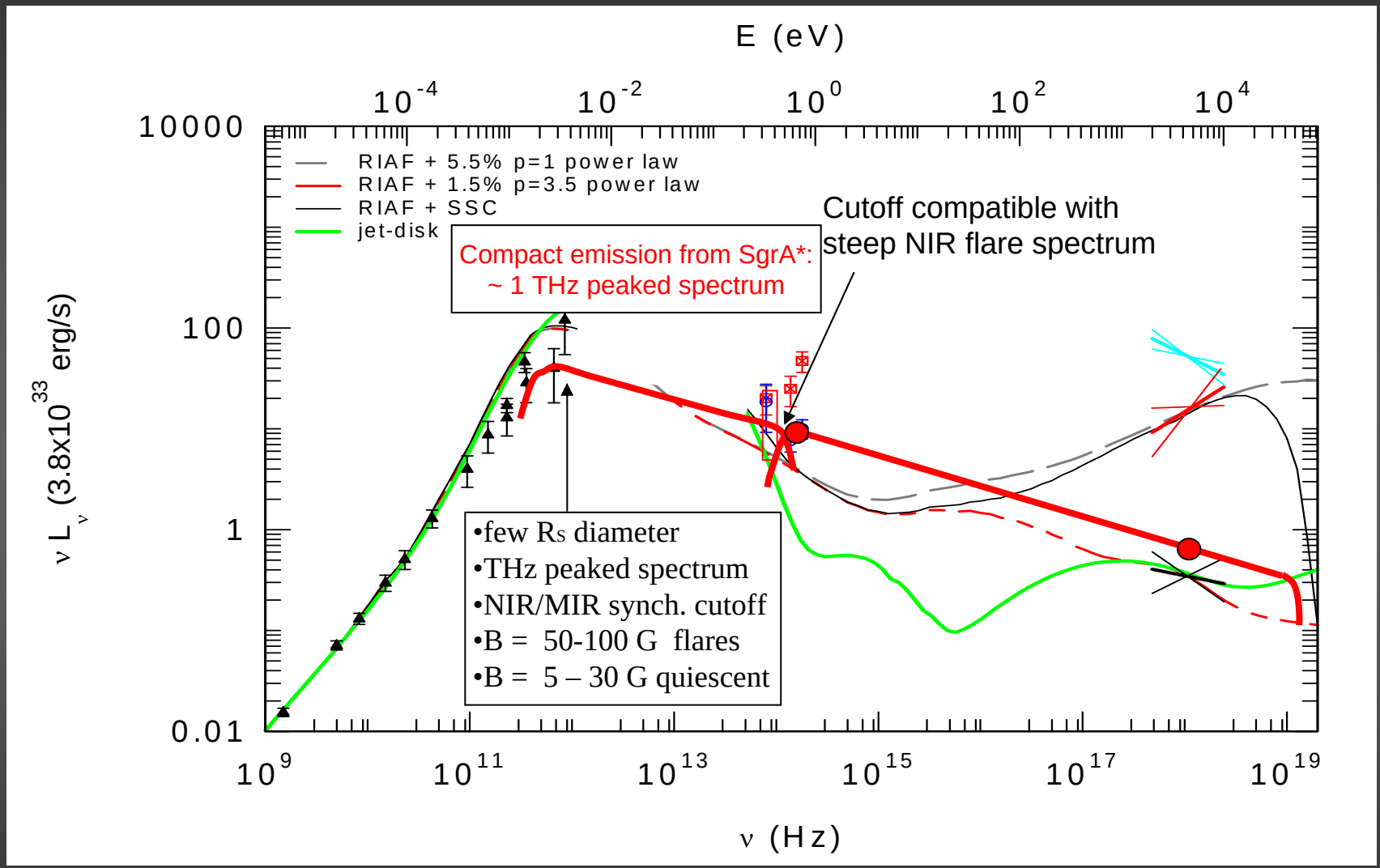
Cutoff may shift towards shorter wavelength: NIR flare spectral index may be flatter

Model consistent with low upper limits in the MIR

See also
Gillessen et al. 2005
Eisenhauer et al. 2005



First simultaneous weak flare and models



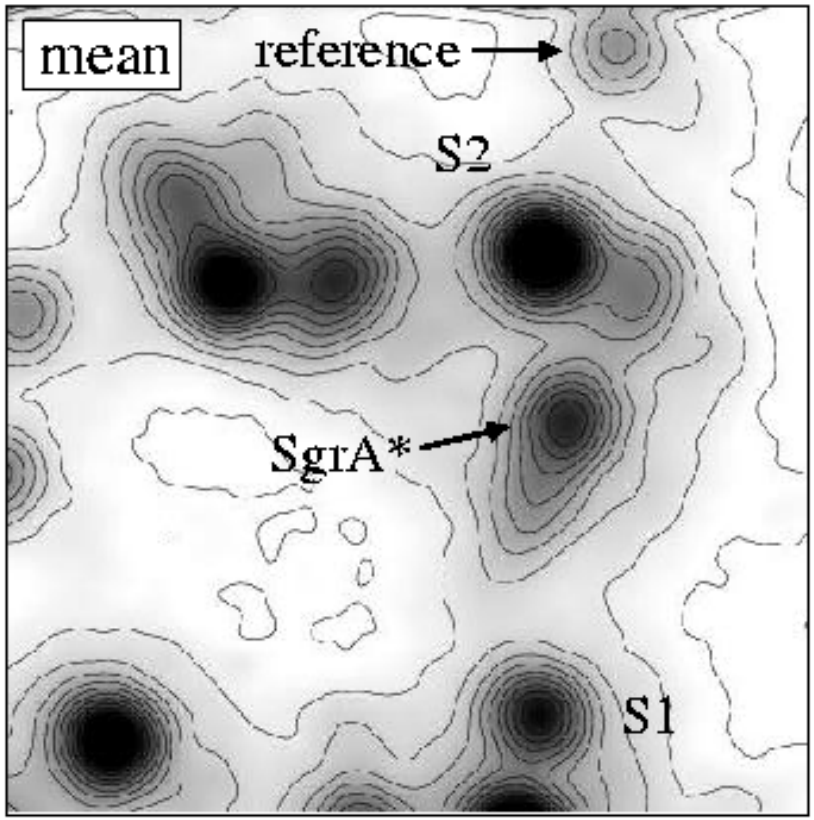
Radio: Zhao, Falcke, Bower, Aitken, et al. 1999-2003
X-ray: Baganoff et al. 2001, 2003, Goldwurm et al. 2003, Porquet et al. 2003,
NIR: Genzel et al. 2003, Ghez et al. 2003
models: Markoff, Falcke, Liu, Melia, Narayan, Quataert, Yuan et al. 1999-2001
SSC model after Marscher (1983) and Gould (1979)

Data and model
Eckart, Baganoff, Morris et al. 2006

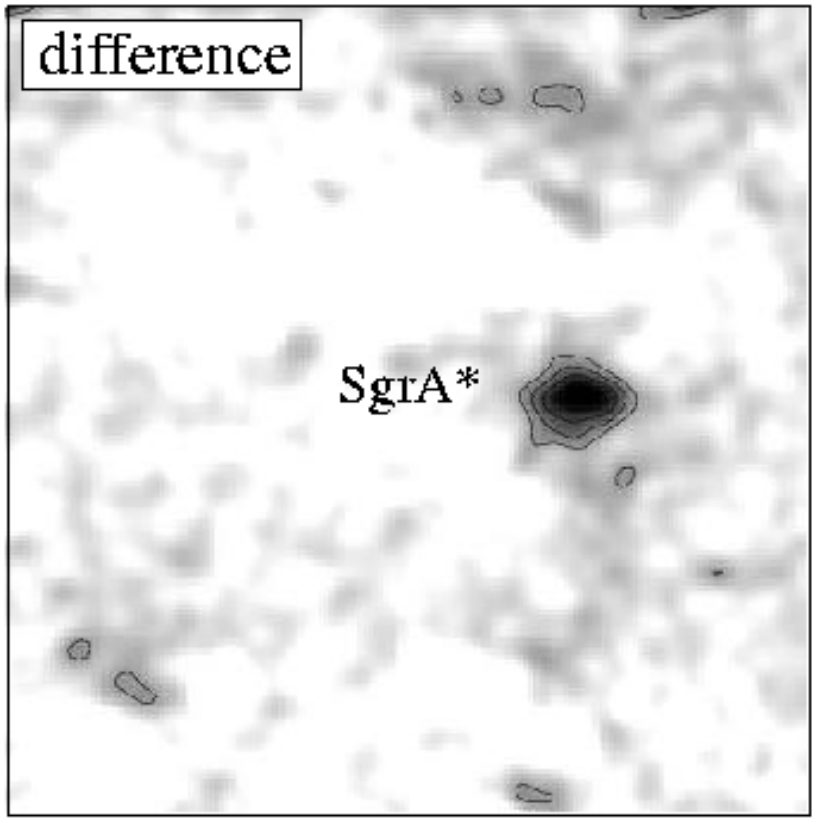
Polarized NIR Flares from SgrA in 2004 and 2005*

Eckart, Schödel, Meyer, Ott, Trippe, Genzel 2006 A&A

NIR Polarized Flux Density from SgrA*



mean flux at 0 and 90 degree

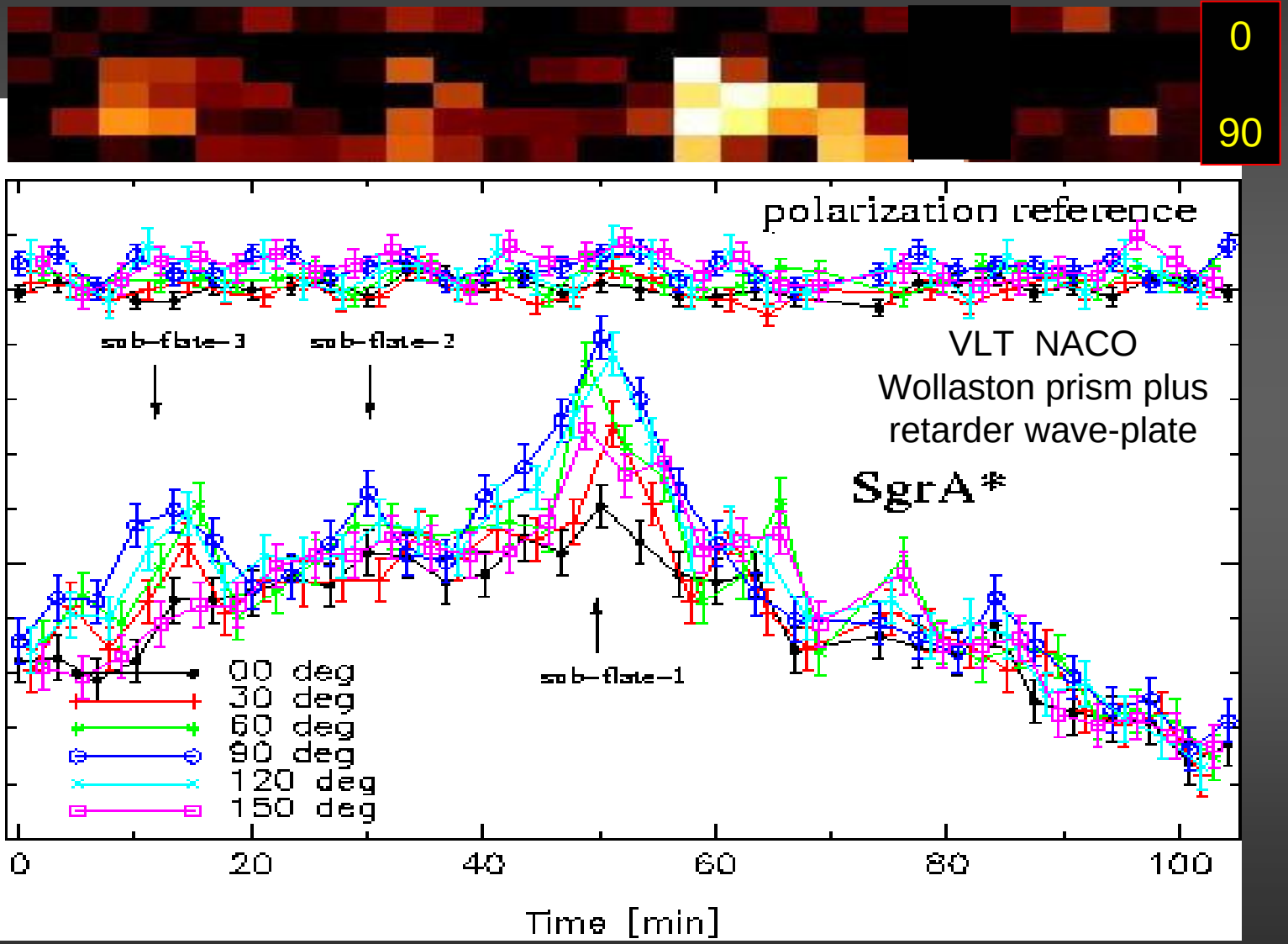


differential flux between 90 and 0 degree

July 2005: VLT NACO Wollaston prism plus retarder wave-plate

2005

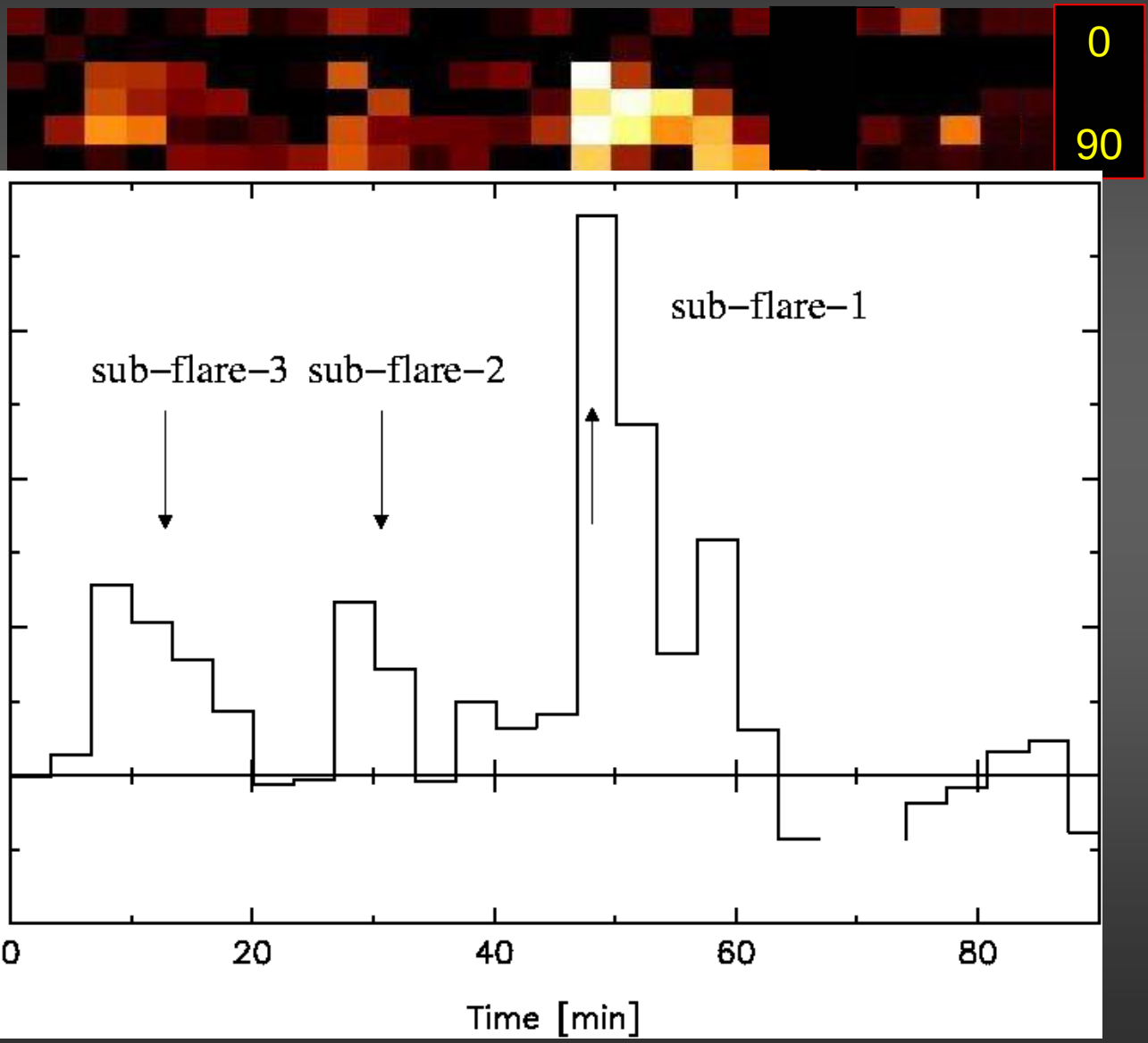
NIR Polarized Flux Density from SgrA*



Eckart, Schödel, Trippe, Ott, Genzel

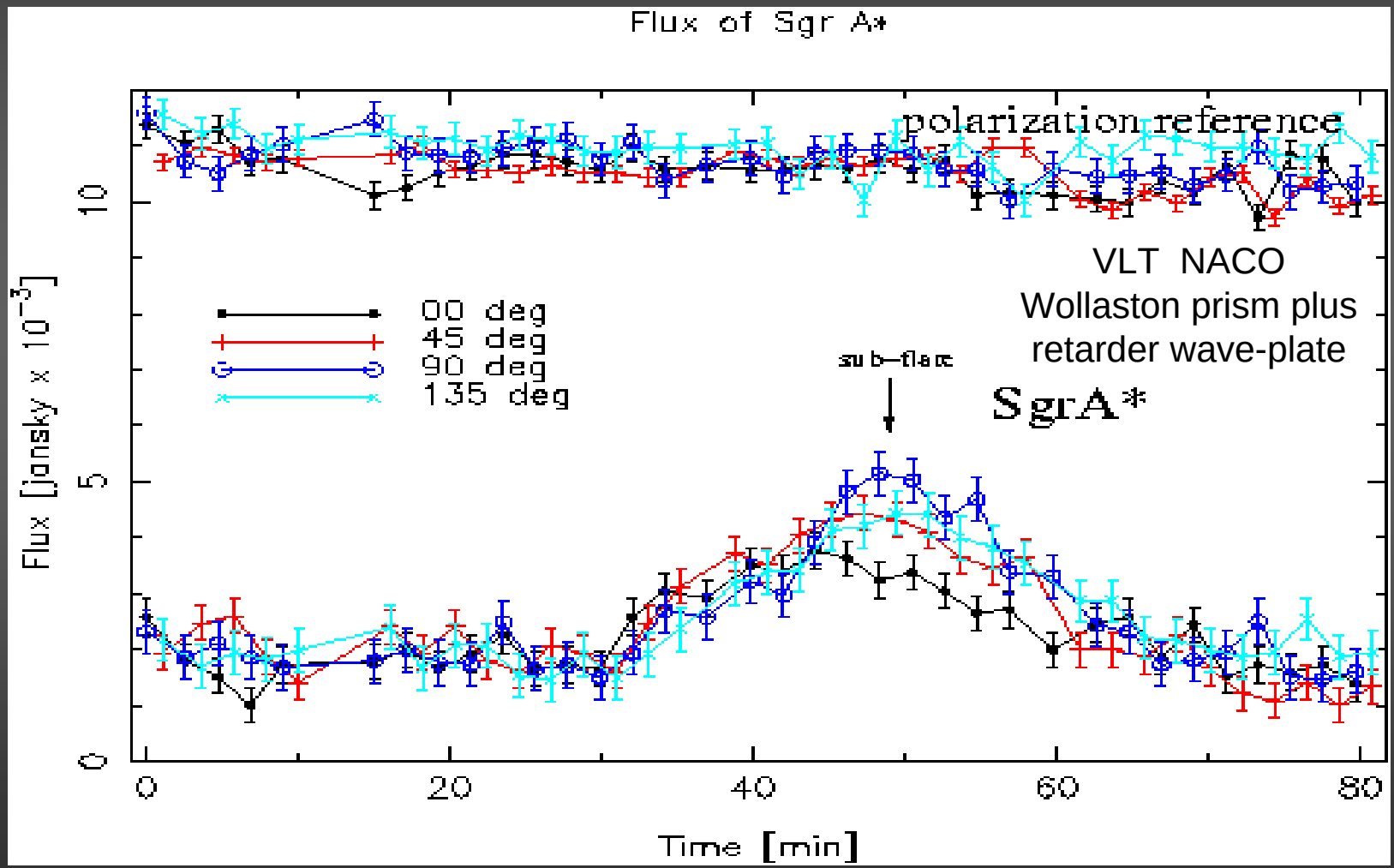
2005

Polarized Flux at 90 degrees



2004

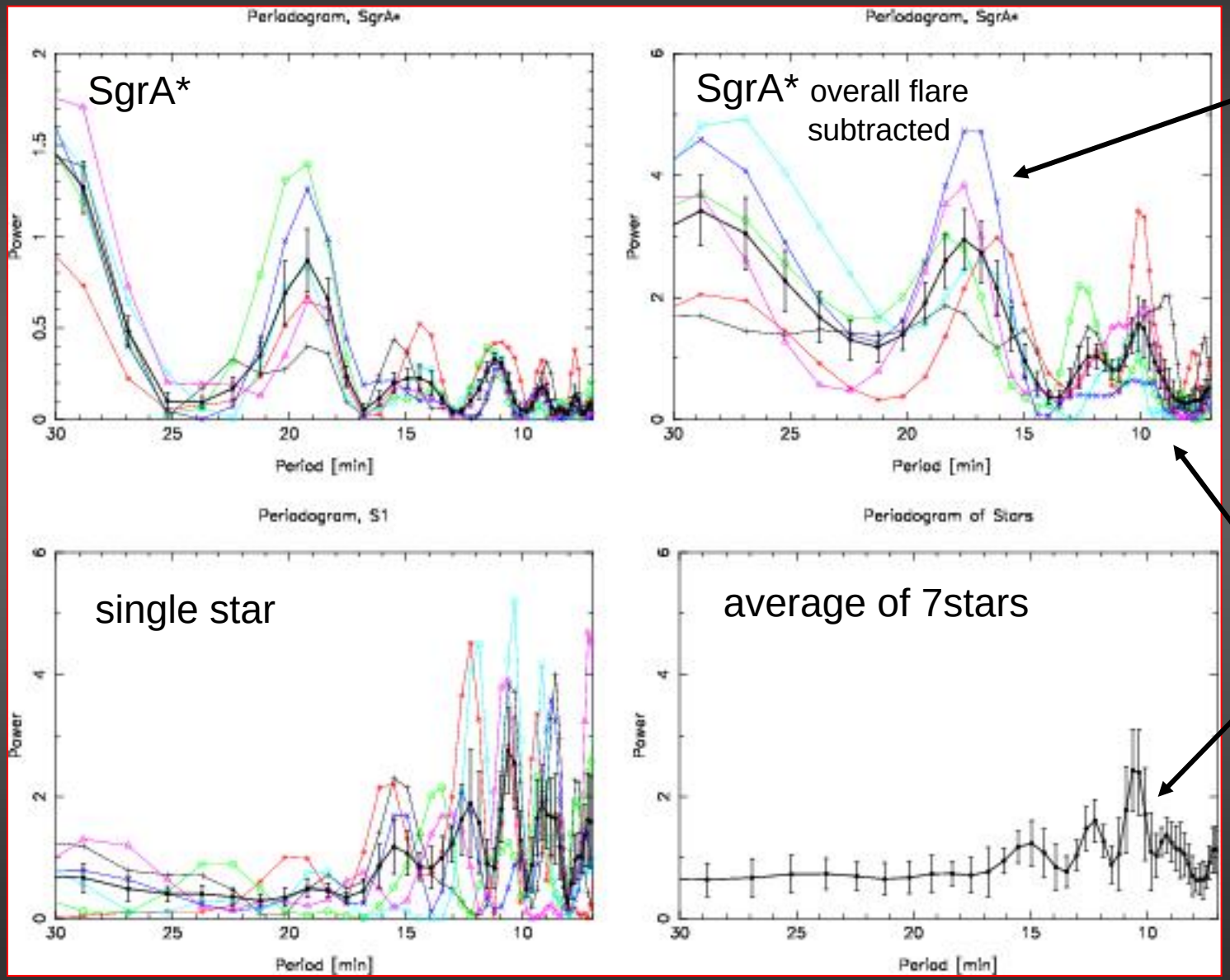
NIR Polarized Flux Density from SgrA*



Eckart, Schödel, Trippe, Ott, Genzel

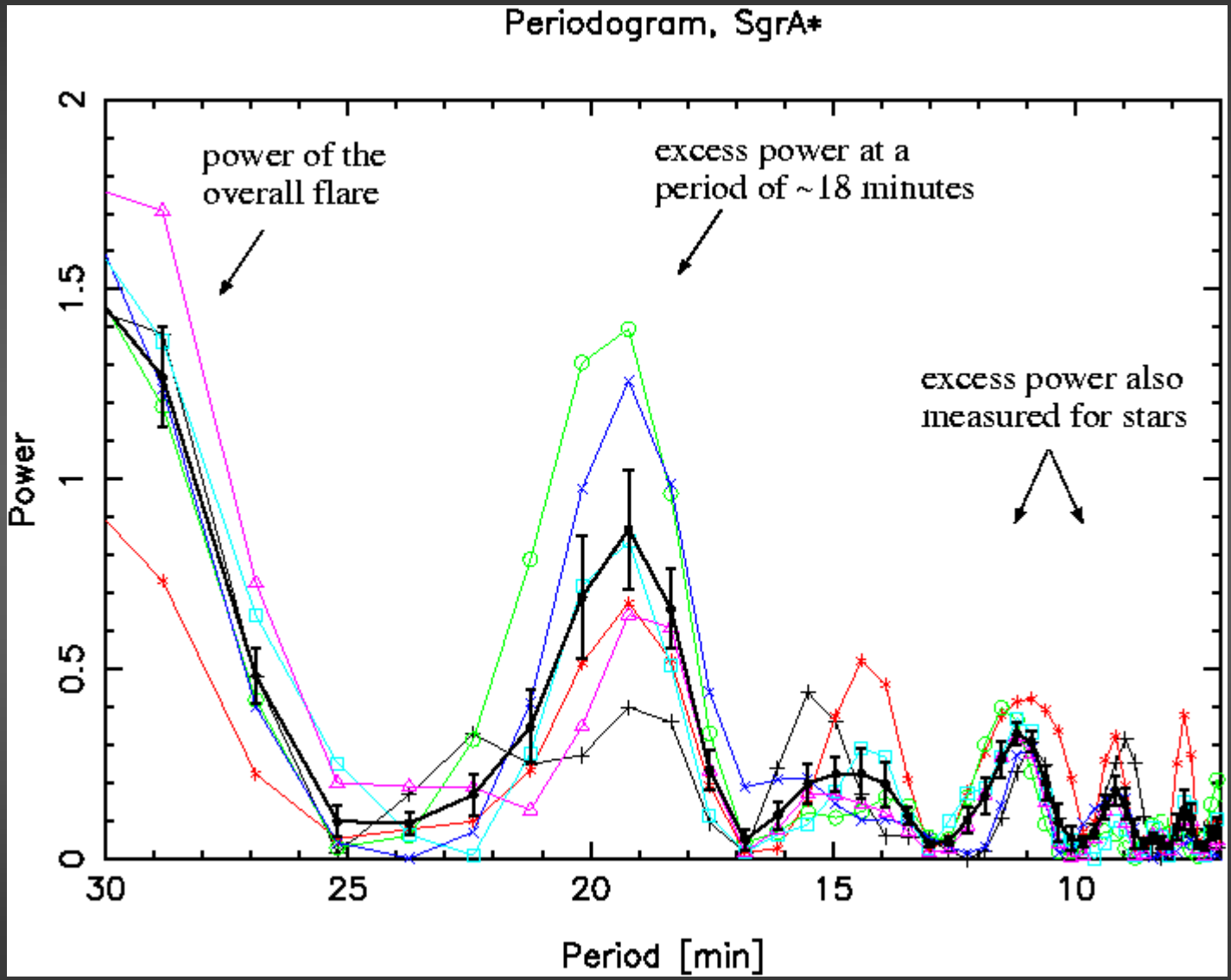
2005

NIR Polarized Flux Density from SgrA*



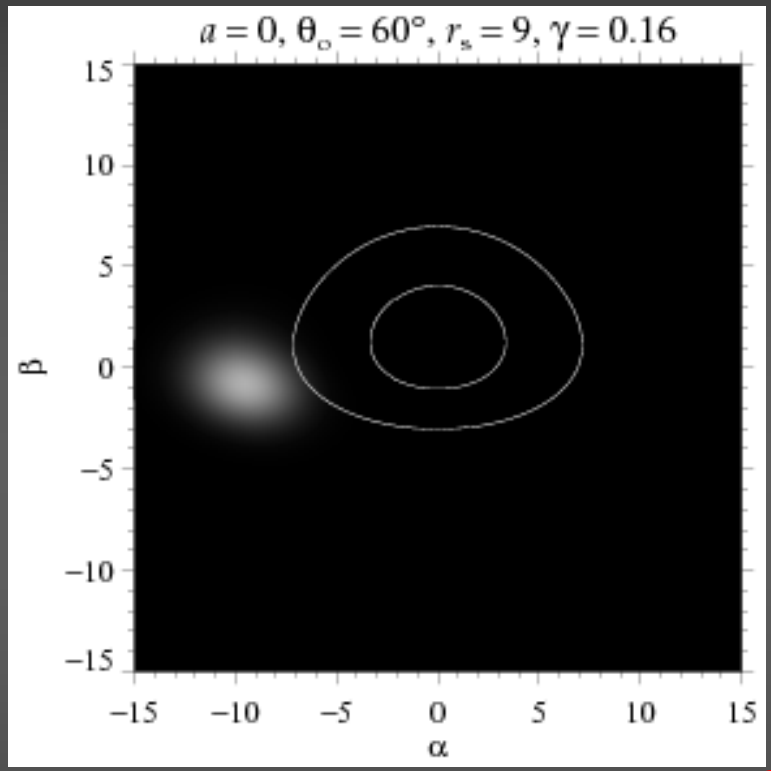
signifiant excess power in SgrA* at ~18min

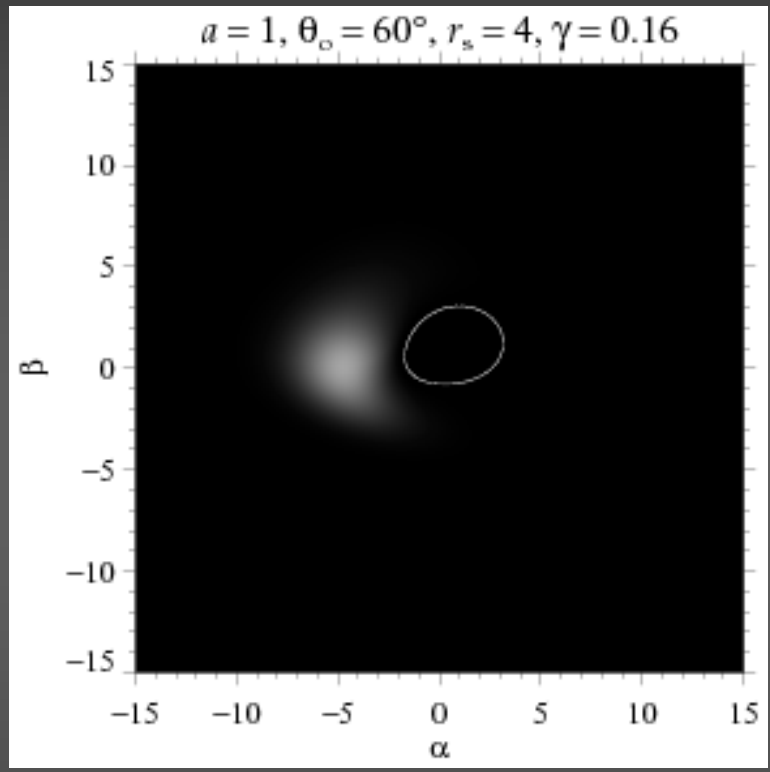
weak power in stars and SGrA*


Periodogram, SgrA*
power of the
overall flare
excess power at a
period of ~18 minutes
excess power also
measured for stars
Power
0
0.5
1
1.5
2
30
25
20
15
10
Period [min]

Radiation from a Temporal Accretion Disk

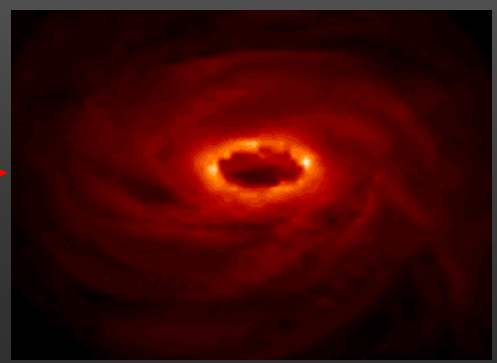
NIR Polarized Flux Density from SgrA*





Dovciak et al. 2006

Goldston, Quataert & Igumenshchev 2005, ApJ 621, 785



~4min prograde
~30min static
~60min retrograde
for 3.6x10**6Msol

see also Broderick & Loeb 2005 astro-ph/0509237
Broderick & Loeb 2005 astro-ph/0506433

Cyclic Accretion Disk Modes ?

Cyclic modes associated with accretion disks are well known QPO from (Nowak & Lehr 1998):

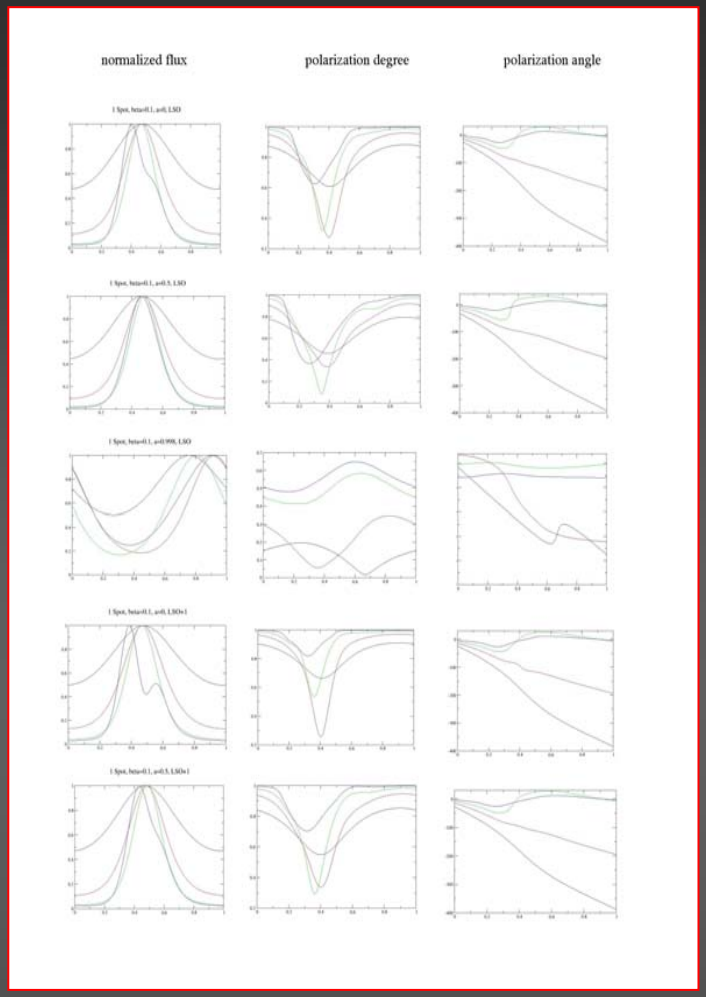
- Kepler orbital motion
- Lense-Thirring Precission
- vertical and ...
- radial epicyclic oscillation modes

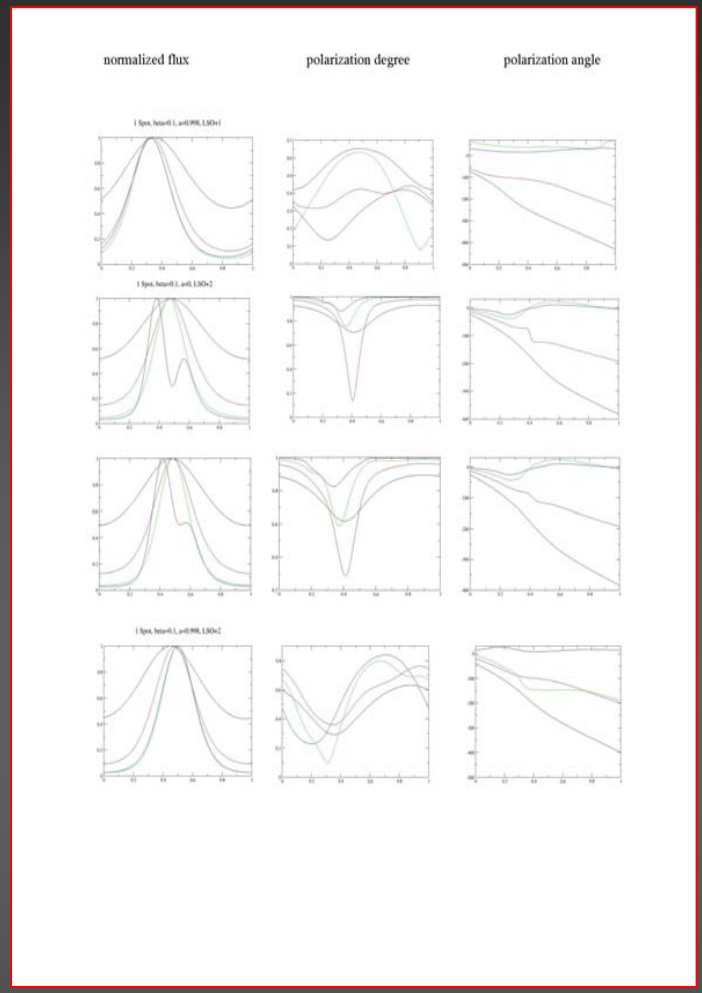
They depend on the dimensionless spin parameter a=J/M and are of the order of a few 100Hz for 10 solar mass stellar BHs and about 0.6mHz for the GC MBH.

Aschenbach et al. (2004a,b) derive ~3.3 million solar masses and a~0.992 as possible solutions for the Galactic Center.

If emission is not associated with LSO then17min period may represend a lower frequency mde.

~4min prograde
~30min static
~60min retrograde
for 3.6x10**6Msol



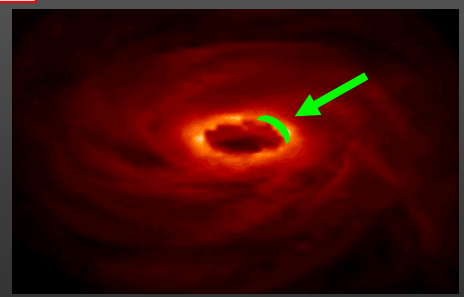


NIR Polarized Flux Density from SgrA*

total power,
degree of polarization
and position angle from
model calculations

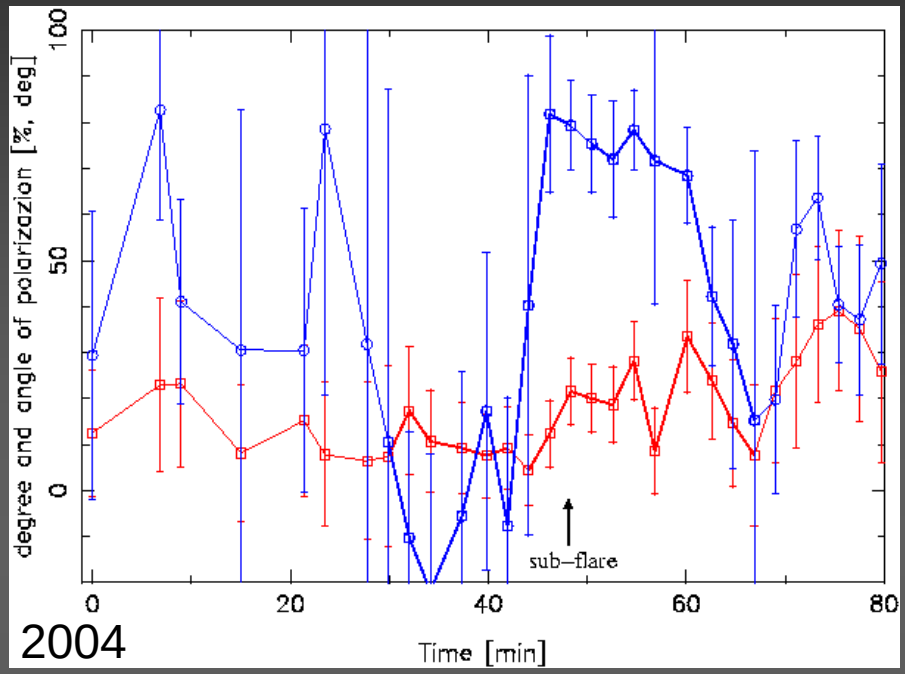
a=0.5 (t~20 min),
i=45,
r=near LSO
Blob, σ=1.1Rs

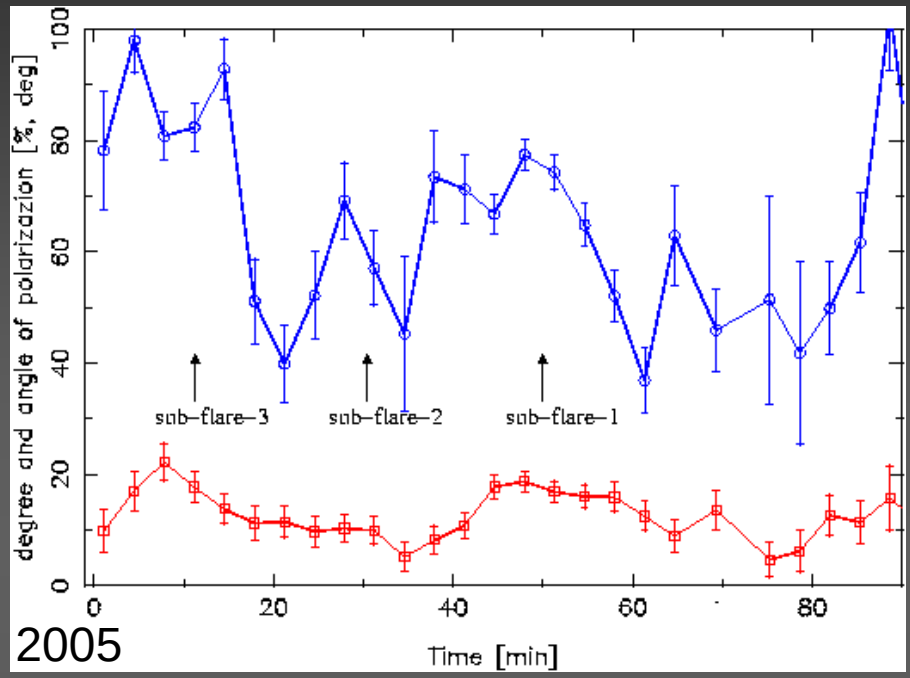
flat spots
on disk



Code: Dovciak M., Karas, V., & Yaqoob, T., ApJS July 2004, 153, 205-221

Position angle of the polarized emission from SgrA* ?





position angle degree of polarization

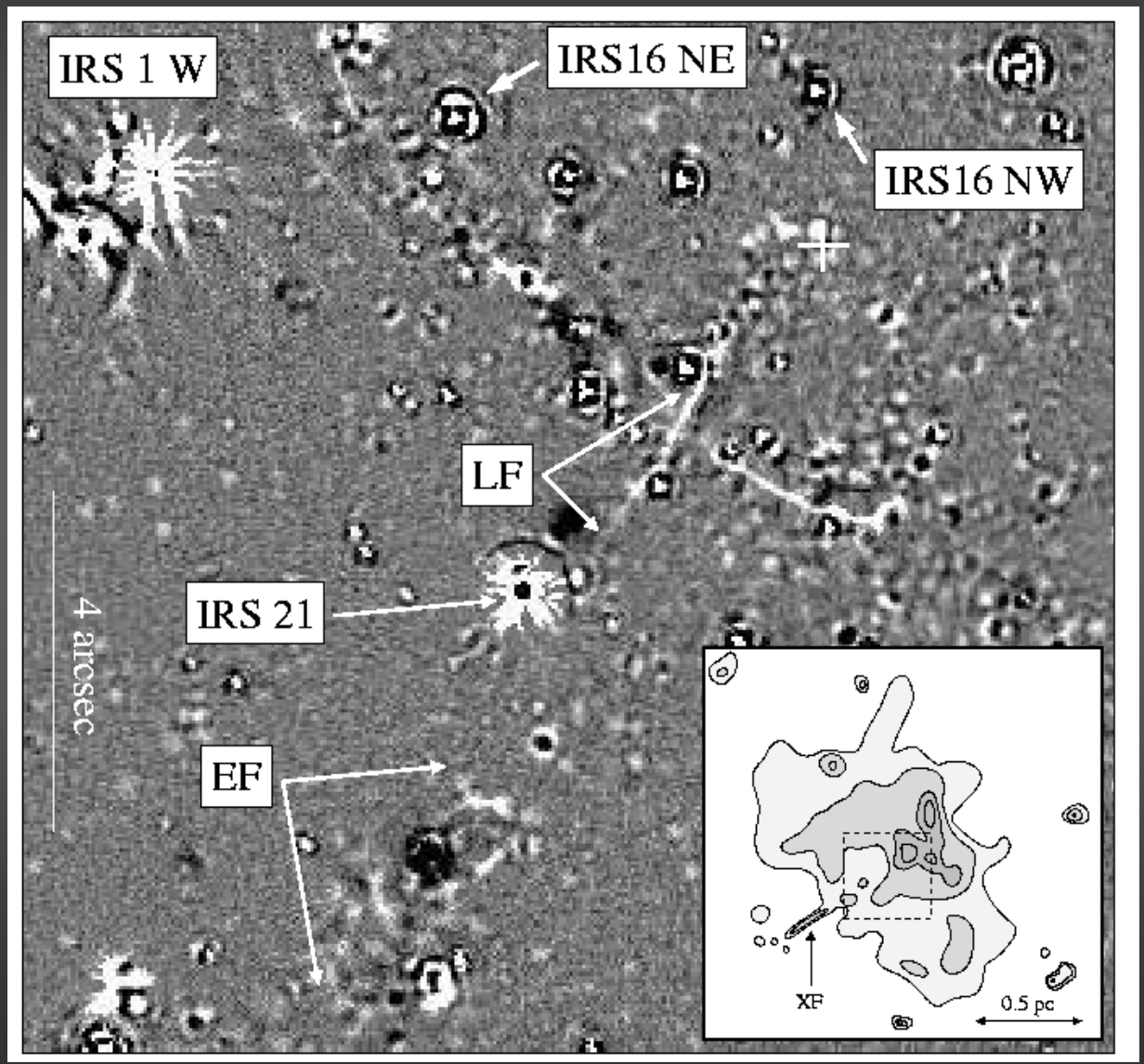
The polarization angle varies about a value of 60+/-20 indicating that this would correspond to the PA a accretion disk – if excistent – and if the mean PA of the E-vector is perpendicular to the disk.

If the emission is due to a jet the PA of the jet is less clear:

Pollack, Taylor & Zavala 2003 find a flat distribution with a tendency of a perpendicular jet and E-vector

Rusk 1988 and Gabuzda et a. 2000 find a weak indication for parallel orientations in stronger beamed souces

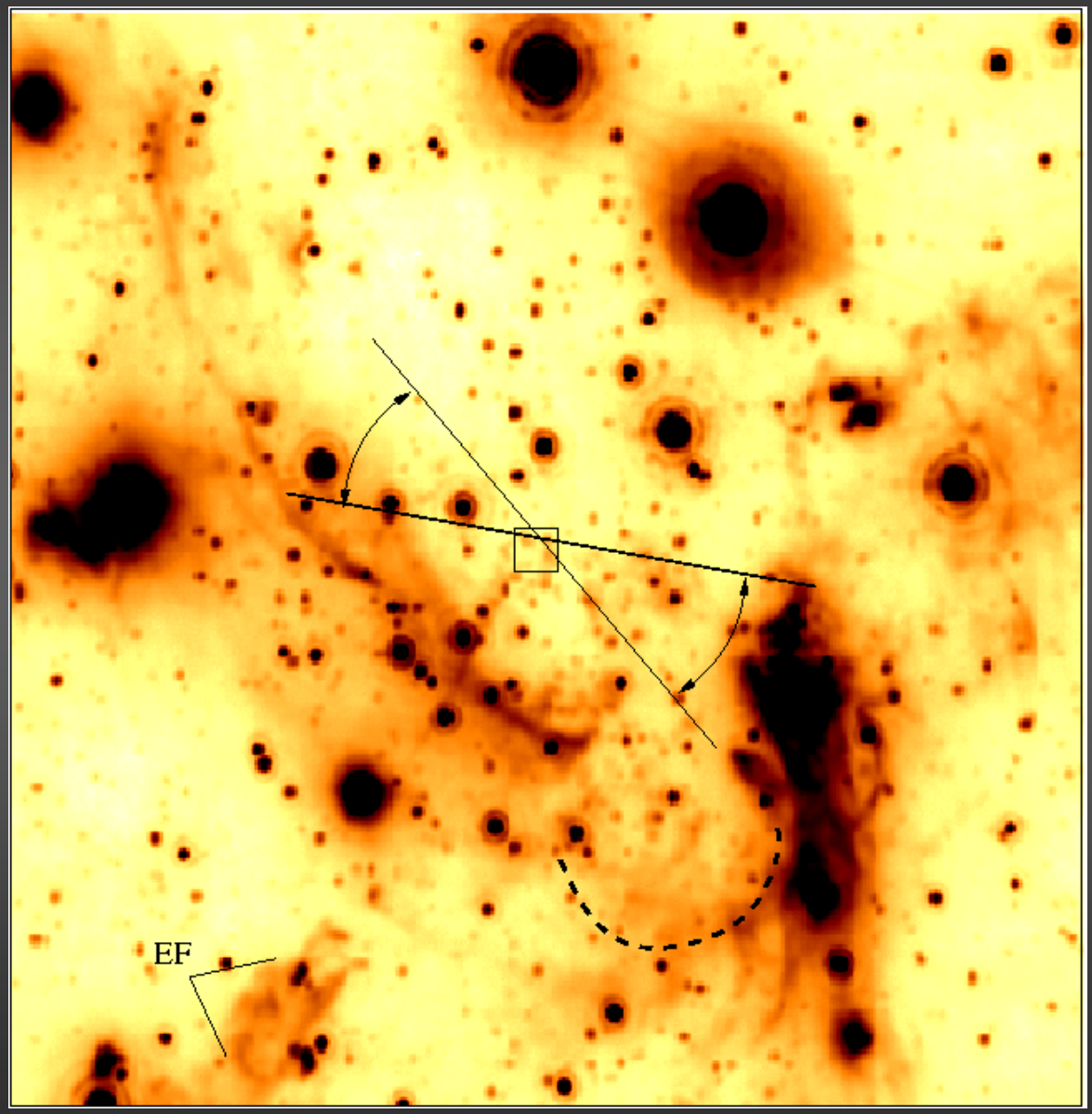
A jet or wind emerging from SgrA* ?



Two possible jet features
LF in the IR and
XF in the X-ray
(Morris et al. 2004).

Position angles:
LF ~30
XF~60
LF is curved
LFand XF are not
colinear.

A jet or wind emerging from SgrA* ?

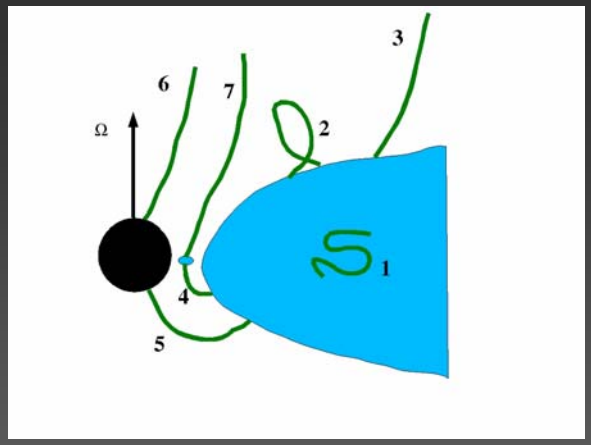


The central 0.5x0.5 square parec at 3.8 μm.

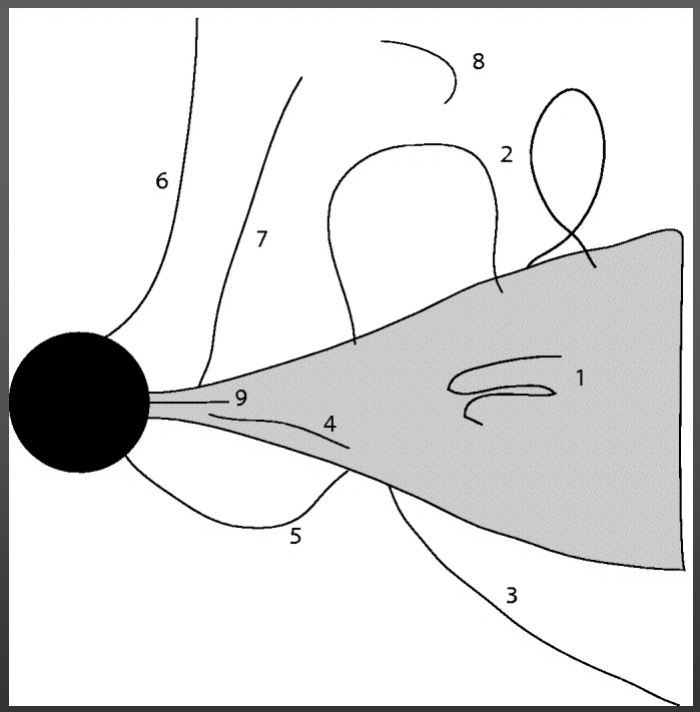
E-vector PA of 60+/-20 with respect to prominent structures

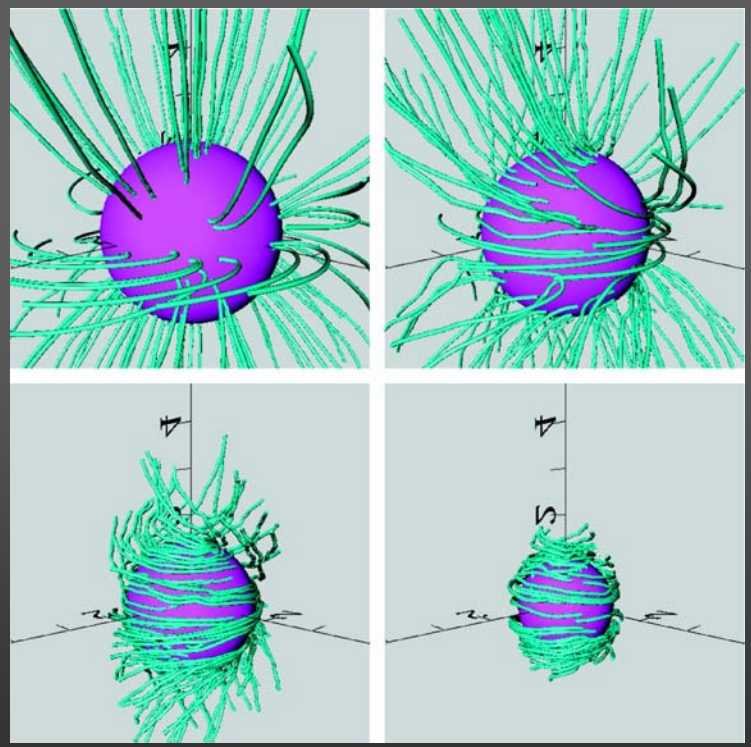
What Magnetic Fields Can Do

NIR Polarized Flux Density from SgrA*



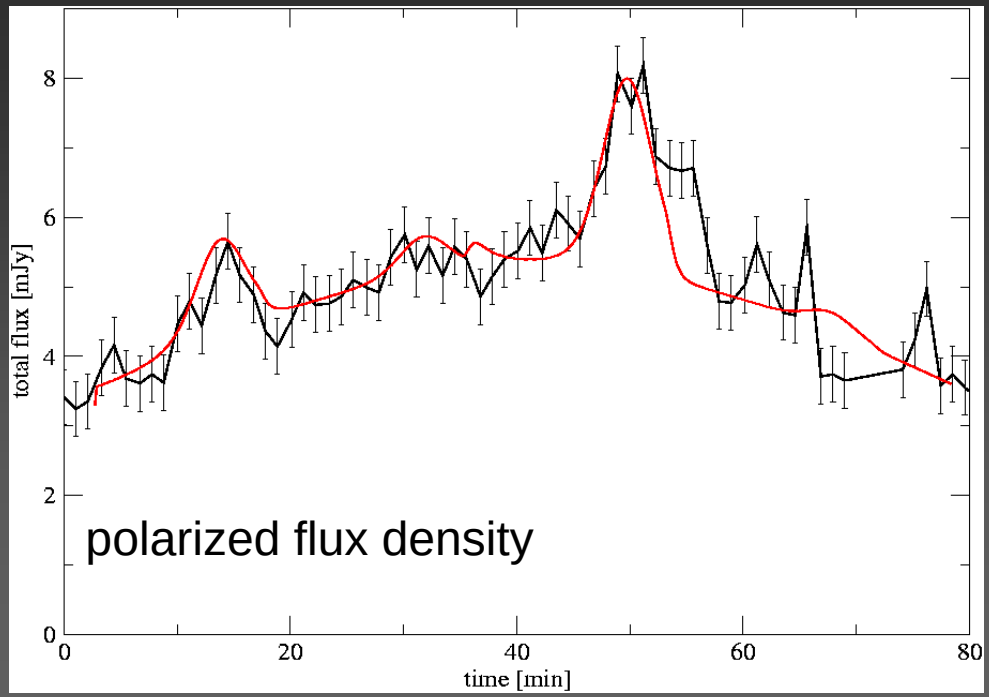
Blandford , 2002 in Lighthouses of the Universe

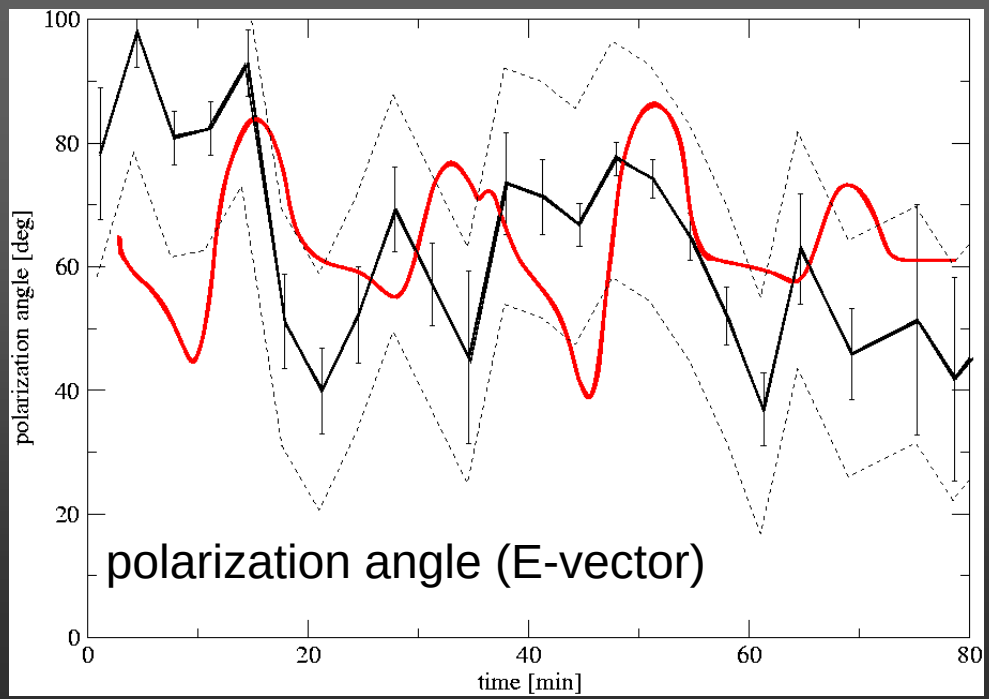


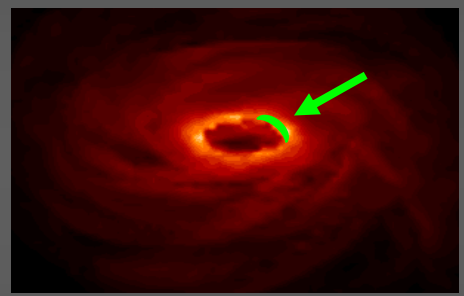


Hirose, Krolik, De Villiers, Hawley 2004, ApJ 606, 1083

NIR Polarized Flux Density from SgrA*







NIR Polarization Data

Assumption:
Flare activity is due to orbital motion
~20 min quasi-periodicty is relevant

NIR polaization data is in agreement with a~0.5

*General Statement on Variability of SgrA**

NIR Flare Rate

The results of the 2005 session are in agreement with a K-band flare rate of

$$4 \pm 2 \quad flares / day$$

Assumtion:

- characteristic flare length

$$\kappa_0 \sim 100 \pm 30 \,\mathrm{min}$$

- The NIR emission of SgrA* can be described by consecutive flares of that characteristic length

Finding:

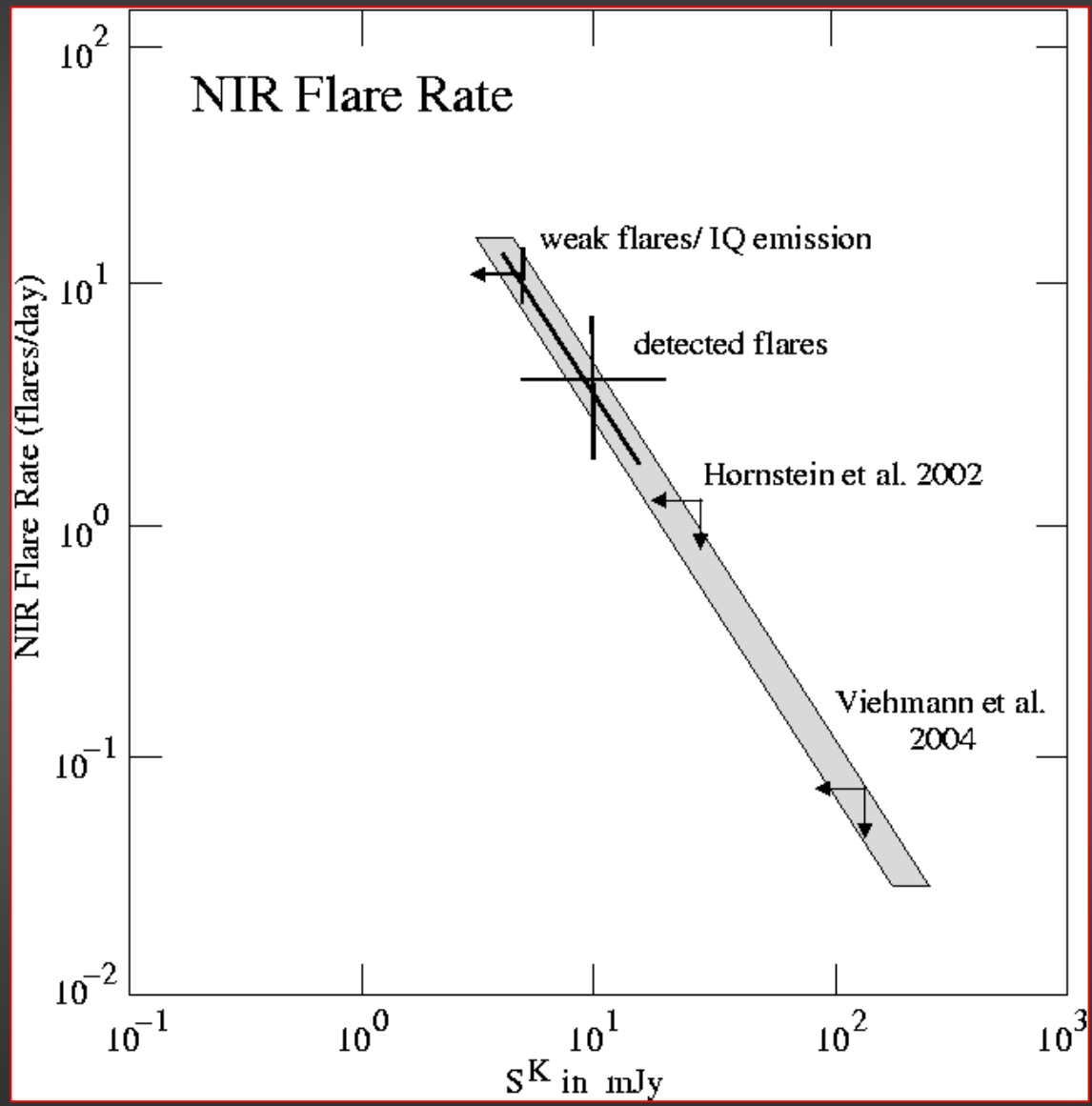
Flare rates and limits lie on a $\varsigma = -1.4 \pm 0.2$ power-law

$$N(A) = \kappa_0 A^{-\varsigma} \kappa_1 \kappa_2$$

$$\kappa_1 = \exp(-A / A_{high})$$

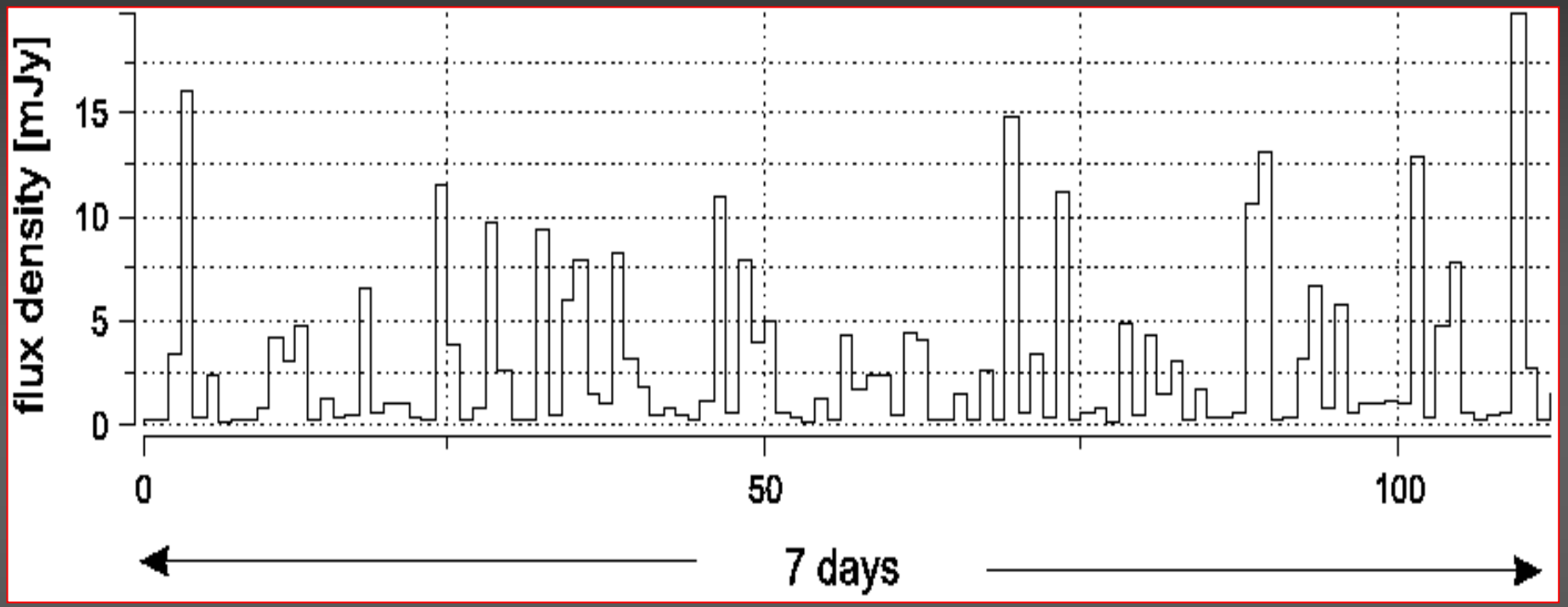
$$\kappa_2 = \exp(-A_{low} / A)$$

Results by Hornstein and Viehmann scaled to 100 min.



value of ζ is independent on value for κ_0

Simulation of SgrA* NIR flare activity



Simulation of the NIR flare activity assuming a characteristic flare length of 100 minutes, a typical flare flux of 10-20 mJy, and a power-law dependency with a power-law index of $\zeta \sim -1.4$

Are there dominant red noise contributions?

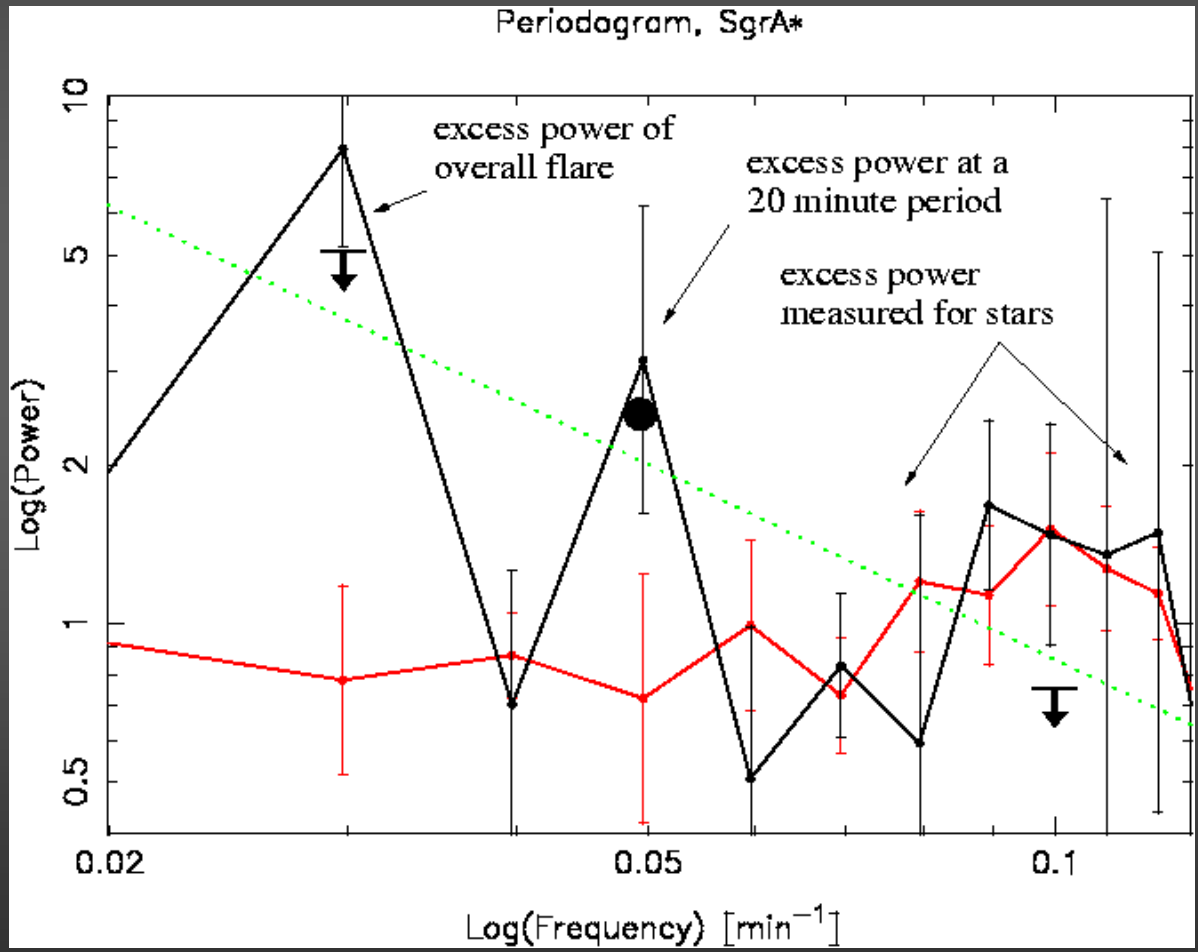
Mauerhan et al. 2005 (in the mm-range for SgrA*) and Benlloch et al. 2001 (X-ray domain for Mrk766) showed that for >10-20 min variablity the variability can be discribe by a red noise power law of the form

$$P(f) \sim f^{-\beta}$$

We find

$$\beta = 1.2 \pm 0.7$$

and therefore no significant indication for dominant red noise contributions in the covered frequency range



Are there Alternatives to the BH Scenario?

Neutrino Ball Scenario

supported by degeneracy pressure

Scaling relation between mass and radius (Munyaneza, Tsiklauri,& Viollier 1999):

$$MR^3 = \frac{91.869\hbar^6}{G^3 m_\nu^8}\left(\frac{2}{g_\nu}\right)^2$$

$$MR^3 = 3\times 10^6 \left(23.18 mpc\right)^3 \left(\frac{17.2 keV}{m_\nu c^2}\right)^8 g_\nu^{-2}$$

For large neutrino masses small radii can be obtained.
However, to explain all nuclear dark masses ranging between 3 million (GC) and 3000 Million (M87) solar masses the putative, as yet unidentified neutrinos must have a mass in the range of 17keV.
Radii for the GC are then of the order of 15mpc
→ Can be excluded for the Galactic Center !

Stellar orbitsnear SgrA* make a universal Fermion ball scenario for extragalactic objects very unattractive

Boson Star Scenario

Torres, Capozziello & Lambiase 2000, Phys.Rev 62, 104012
supported by Heisenberg uncertainty principle

non-interaction Bosons:

Kaup 1968, Ruffini & Bonazzola 1969

$$m = 1GeV, R = 1\,fm, M = 10^{-19} M_o$$

self-interacting Bosons:

Colpi, Shapiro & Wasserman 1986, Torres, Capozziello & Lambiase 2000, Lu & Torres 2003:

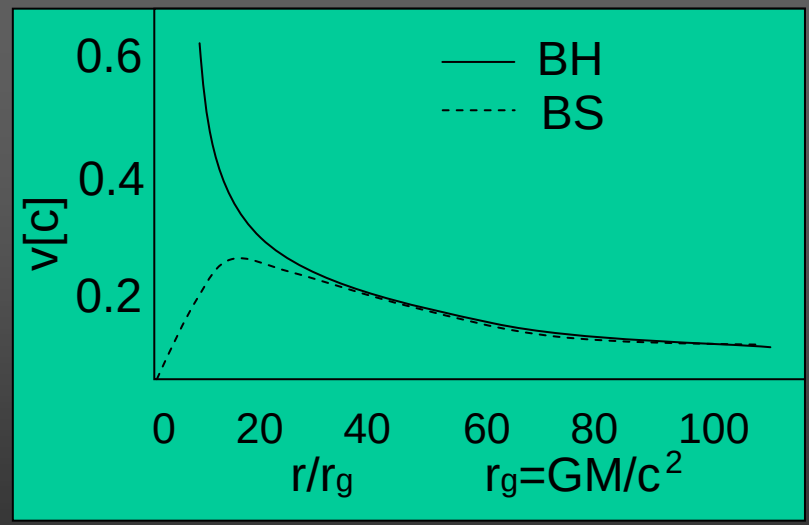
For a large range of hypothetical boson masses much larger total masses within radii of only several times their Schwarzschild radii are possible.

GC:

$$M[10^6] \approx M(x)/m[GeV] \times 10^{-25}$$

$$x = mr, m \approx 3 \times 10^{-26} GeV$$

$$r[pc] \approx x/m[GeV]7 \times 10^{-33}$$



Unlikely to form a stabile configuration at the Galactic Center !

Boson Star Scenario

Assumption:
Flare activity is due to orbital motion close to the LOS with a quasi-periodicty of close to 20 min what is indicated by the NIR data:

For a boson star the oribtal velocity at the BH LOS
Is about 3 times lower than it is for the BH case!

For a non-rotation GC BH the orbital period close to the LOS is about 30 min

A non-rotation boson star can be excluded for the GC

Excluded for MCG-6-30-15 (Lu &Torres 2003) based on Kα line width!

IMBHs

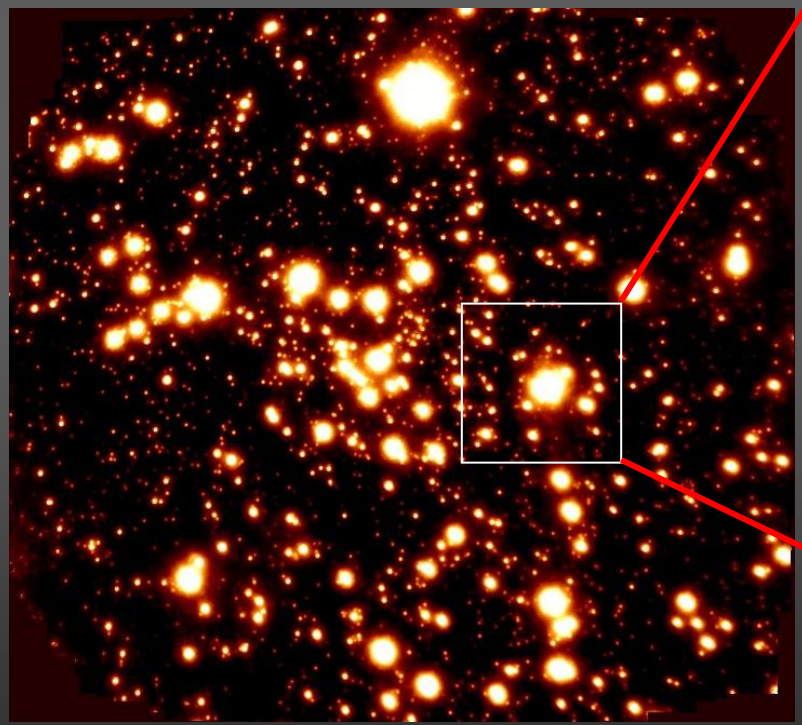
IRS13

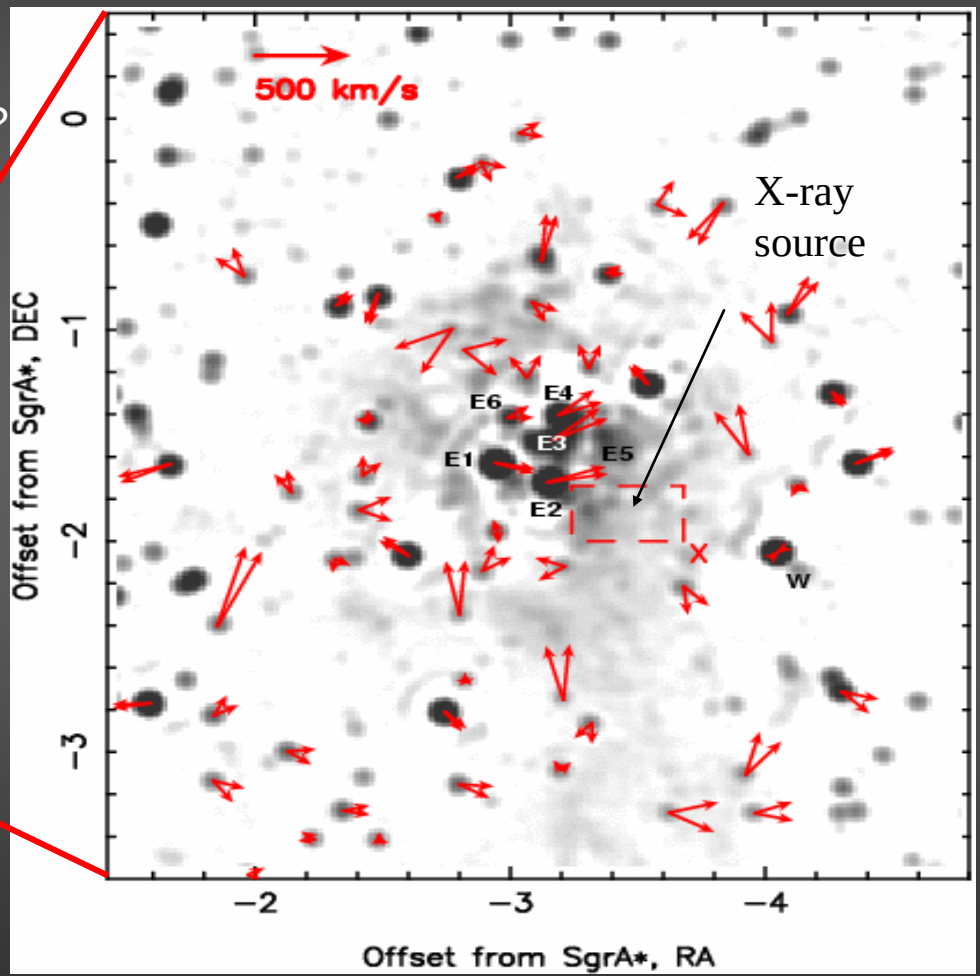
IMBH contained in IRS13?

An IMBH at the Center of the IRS13 Concentration?

IRS13E comprises half a dozen massive stars- possibly a remnent of an infalling stellar cluster (Gerhard (2001),Genzel (2003), Kim & Morris (2003).

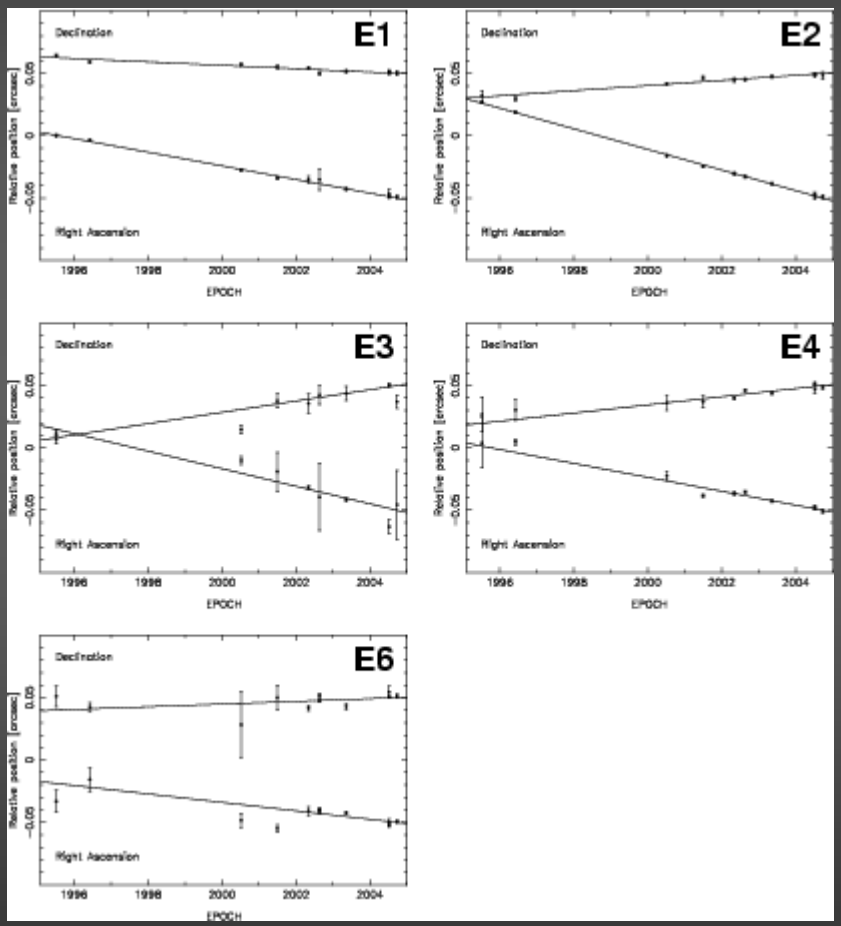
Is there an IMBH at the center of this complex? Hansen & Milosavljevic (2003), Maillard et al. (2004).



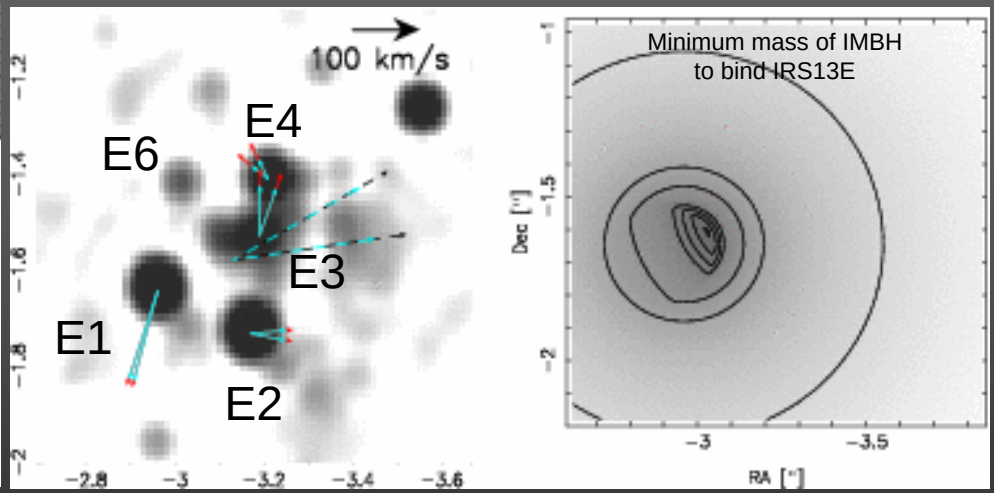


Schödel, Eckart, Iserlohe, Genzel, Ott 2005, ApJ

An IMBH at the Center of the IRS13 Concentration?



Proper motions of individual stars in the IRS13E complex show that the minimum mass to bind IRS13E is 10,000 M_{solar} with no compelling evidence for the actual existence of an IMBH



Schödel, Eckart, Iserlohe, Genzel, Ott 2005, ApJ

MBHs in Galactic Nuclei

Black Hole - Bulge Relationship

Massive Black Holes (MBH) in Nuclei of Galaxies

- Compact dark masses (probably MBHs) in Nuclei of Galaxies (Kormendy and Richstone 1995)

- MBH about 0.006 of bulge mass (Magorrian et al. 1998)

- 3D models of HST data: MBH/bulge=0.002 (Ho 1999)

- 5 to 20 times smaller MBH in Seyferts and PG QSOs via reverberation mapping (Wandel 1999, Ho 1999)?!

-

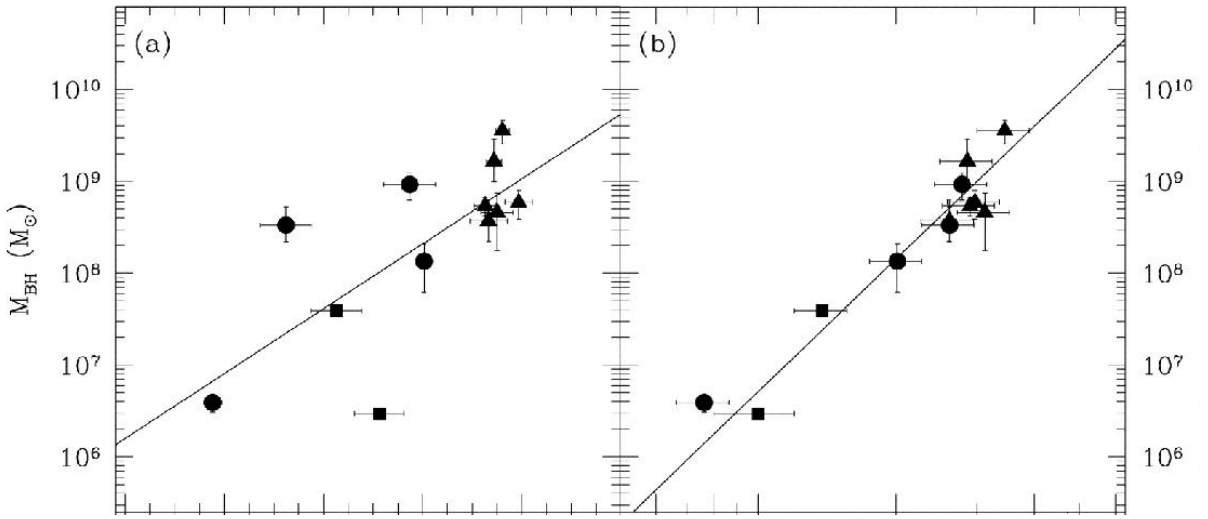
- With the much tighter MBH-σ relation this discrepancy seems to disappear (Ferrarese & Merritt 2000, Gebhardt et al. 2000, Shields et al. 2003)

- Nelson (2000) finds no difference between MBH-σ(OIII) masses and BH masses taken from reverberation methods and proposes to use σ(OIII)=FWHM([OIII])/2.35km/s as surrogate for σ stellar.

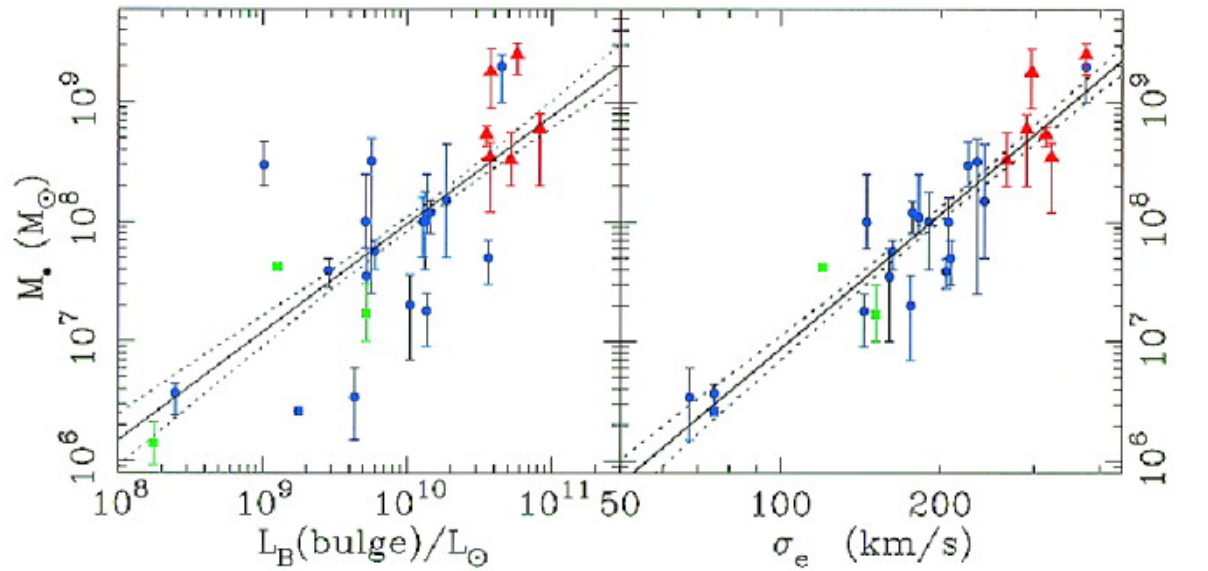
- LOCAL: MBH/bulge =0.0016 Kormendy & Gebhardt (2001)

How does this evolve with redshift??

M-L_{bulge} versus M-σ Relations



Farrese & Merritt 2000



Gebhardt et al. 2000

M-σ Relations

$$M_{BH} = 1.40 M_{sol} \left(\frac{\sigma_*}{200 km/s} \right)^{4.8 \pm 0.5}$$

Merritt & Farrese 2000

$$M_{BH} = 1.20 M_{sol} \left(\frac{\sigma_*}{200 km/s} \right)^{3.8 \pm 0.3}$$

Gebhardt et al. 2000

$$M_{BH} = 1.35 M_{sol} \left(\frac{\sigma_*}{200 km/s} \right)^{4.02}$$

Tremaine et al. 2002

Stellar dynamics is hard. How can one extend this to higher z ??

Massive Black Holes (MBH) in Nuclei of Galaxies

- Compact dark masses (probably MBHs) in Nuclei of Galaxies (Kormendy and Richstone 1995)

- MBH about 0.006 of bulge mass (Magorrian et al. 1998)

- 3D models of HST data: MBH/bulge=0.002 (Ho 1999)

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- LOCAL: MBH/bulge =0.0016 Kormendy & Gebhardt (2001)

How does this evolve with redshift ??

Formation of Massive Black Holes (MBH)

Who knows how it got started??

Quasars at z>6 (e.g. Becker et al. 2001);
10**9 Msol BHs only 10**6 yrs after Big Bang (e.g. Hainman & Loeb 2001)

•Yu & Tremaine (2002) find that half the BH mass is accreted before z~1.8 and only 10% before z=3.

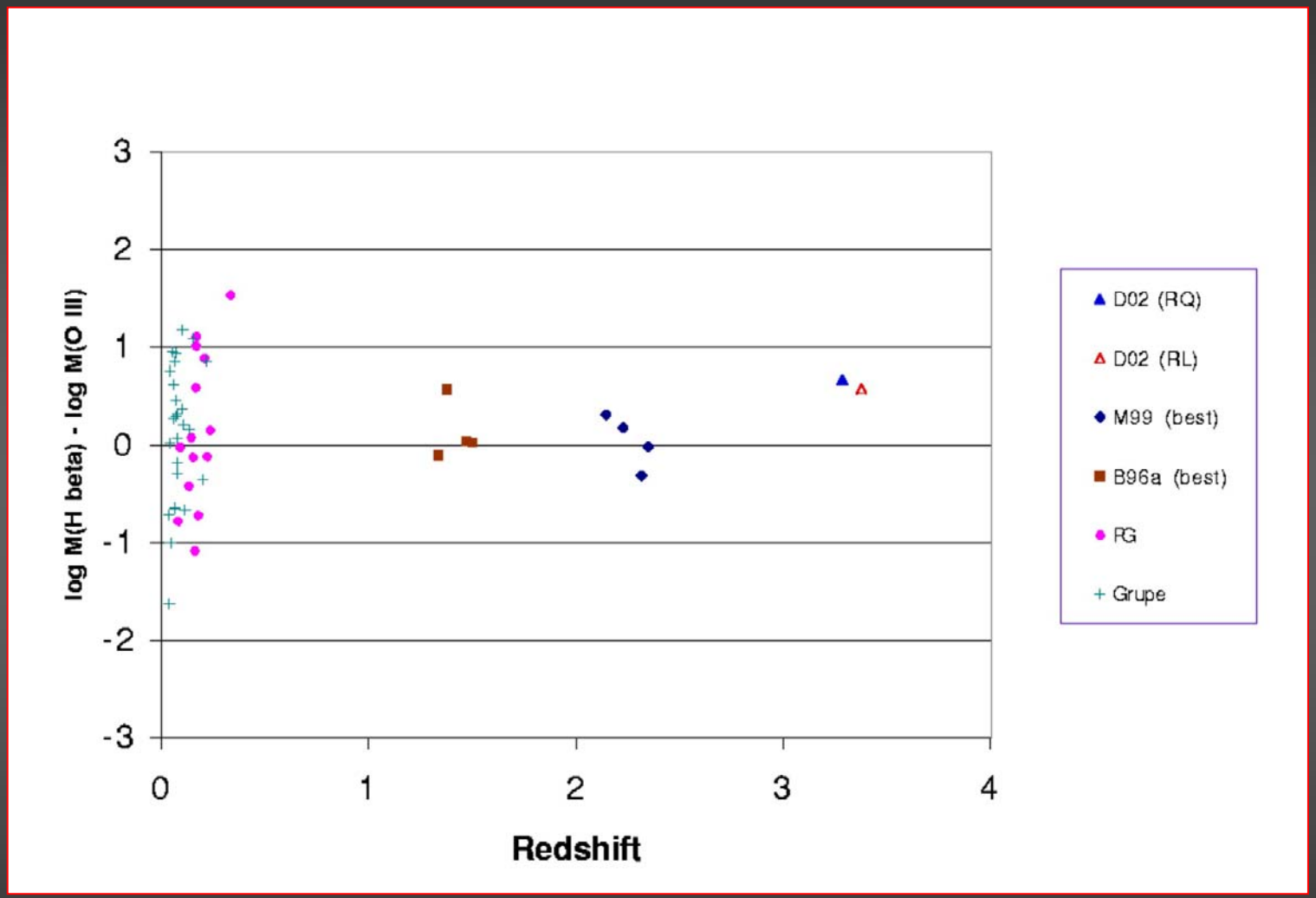
•Shields et al. (2003) use FWHM([OIII]) to determin MBH at high redshifts. Form log(MBH(Hβ)-MBH([OIII]))~0 between 0<z<3.5 they conclude: "... black holes typically grow contemporaneously with their host-galaxy bulges or else ... both are well formed by z~3".

Problem: nuclear outflows?!

•Follows: MBH-s relation is obeyed by massive QSOs even at times at which much of the accretion lies in their future.

Bromm & Loeb (2003): In dwarfs at T>10**4 K virial temperatures and UV suppressed H2 formation tend to form binary (few million Msol) black holes.

M-σ Relation as a function of z



Shields et al. 2003

Formation of Massive Black Holes (MBH)

Who knows what happened at the beginning??

•Yu & Tremaine (2002) find that half the BH mass is accreted before z~1.8 and only 10% before z=3.

•Shields et al. (2003) use FWHM([OIII]) to determin MBH at high redshifts. Form log(MBH(Hβ)-MBH([OIII]))~0 between 0<z<3.5 they conclude: "... black holes typically grow contemporaneously with their host-galaxy bulges or-else ... both are well formed by z~3".

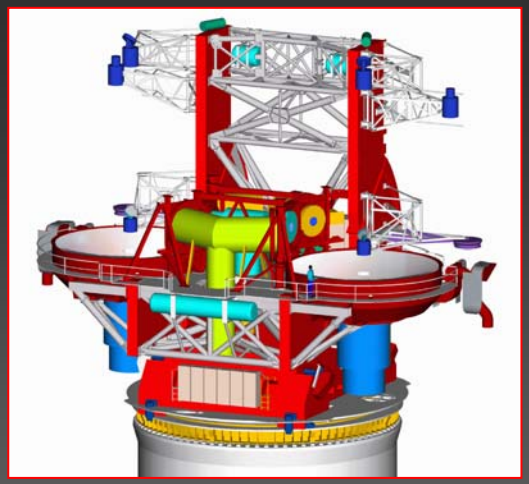
•Follows: MBH-s relation is obeyed by massive QSOs even at times at which much of the accretion lies in their future.

How do they look like?

Bromm & Loeb (2003): In dwarfs at T>10**4 K virial temperatures and UV suppressed H2 formation tend to form binary (few million Msol) black holes.

Future Experiments

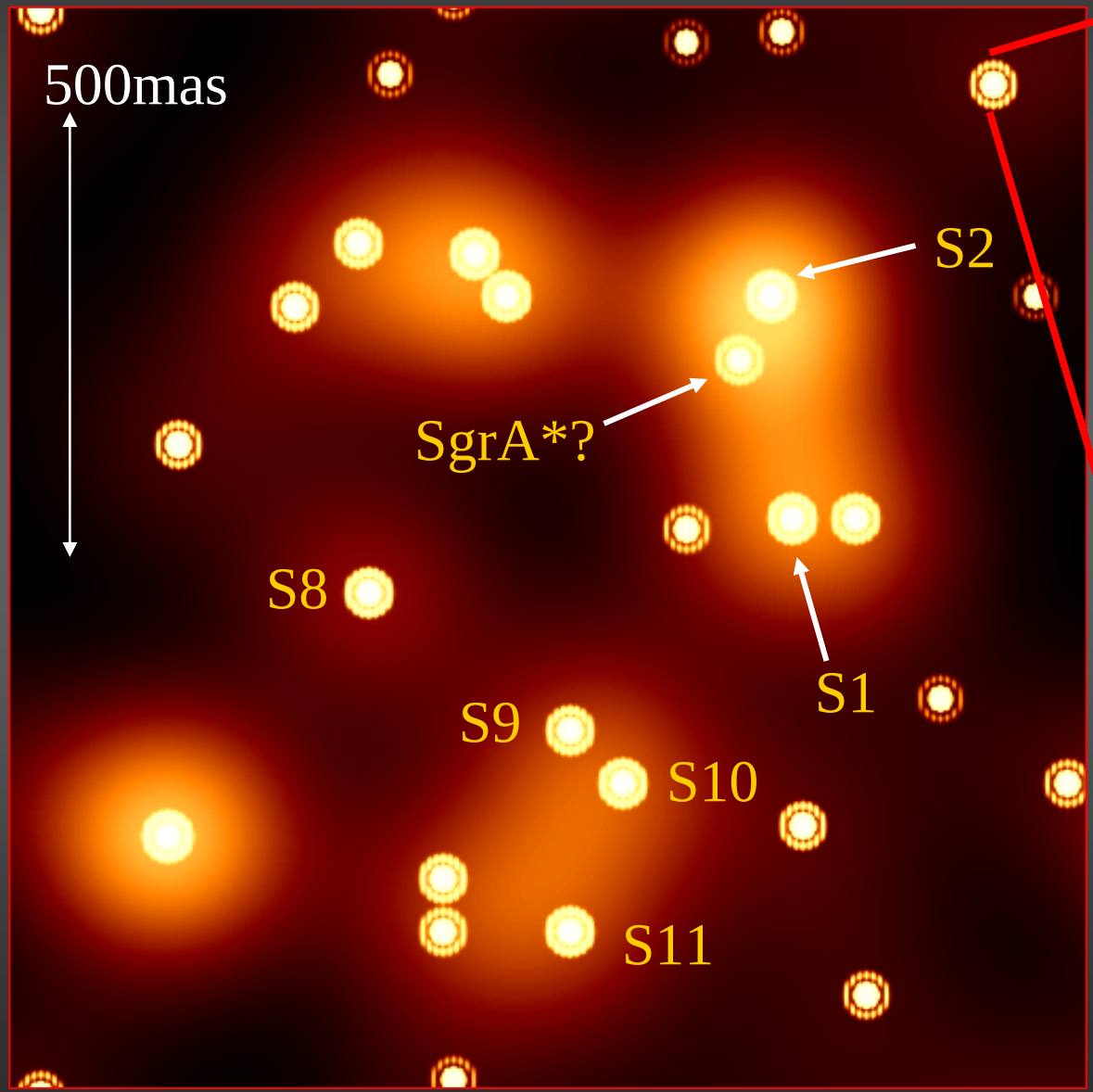
Angular Resolutions of Interferometers under Construction at 2μm Wavelength

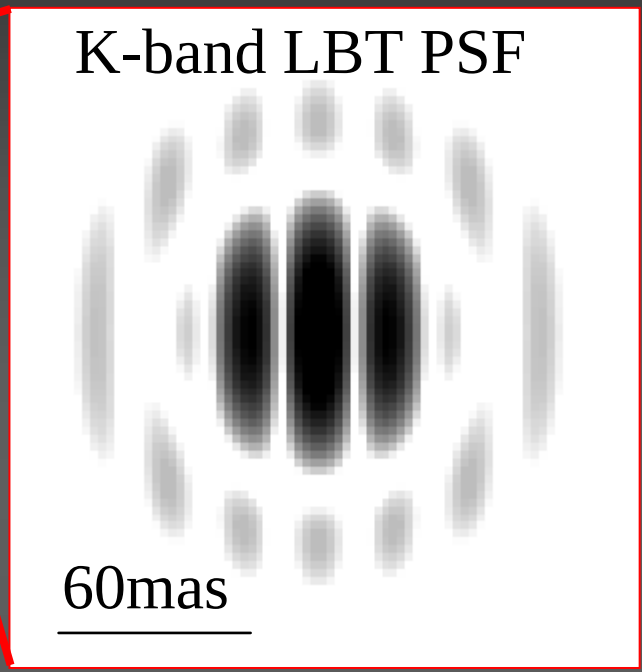


	Baseline	Res.	FOV	
LBT	14.4m	30 mas	1 arcmin	
Keck	85 m	6 mas	two channels	
VLTI	200 m	2.5 mas	1 arcsec	two channels

Rubilar & Eckart 2001

The Galactic Center



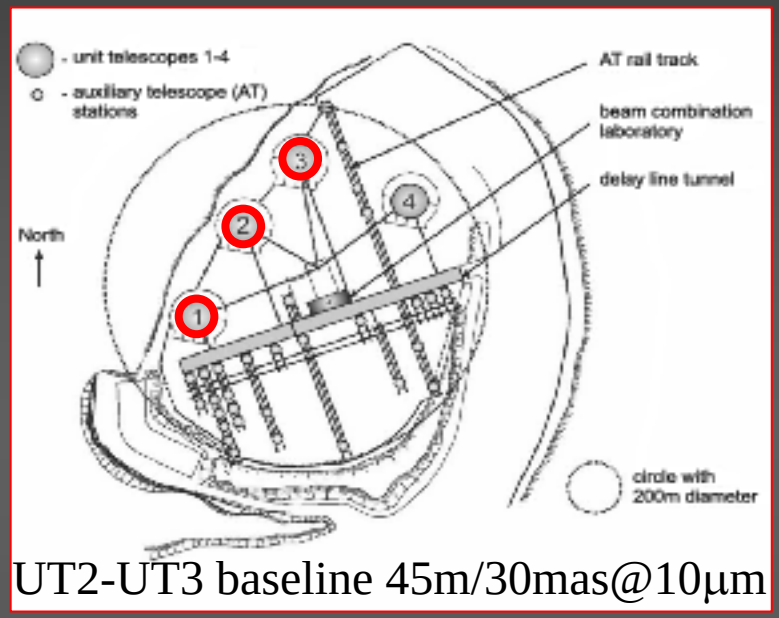


Brighter sources in the the SgrA* cluster as seen with the LBT interferometer (short exposure) at 2μm and a ~50% strehl ratio.

Interferometry with VLTI

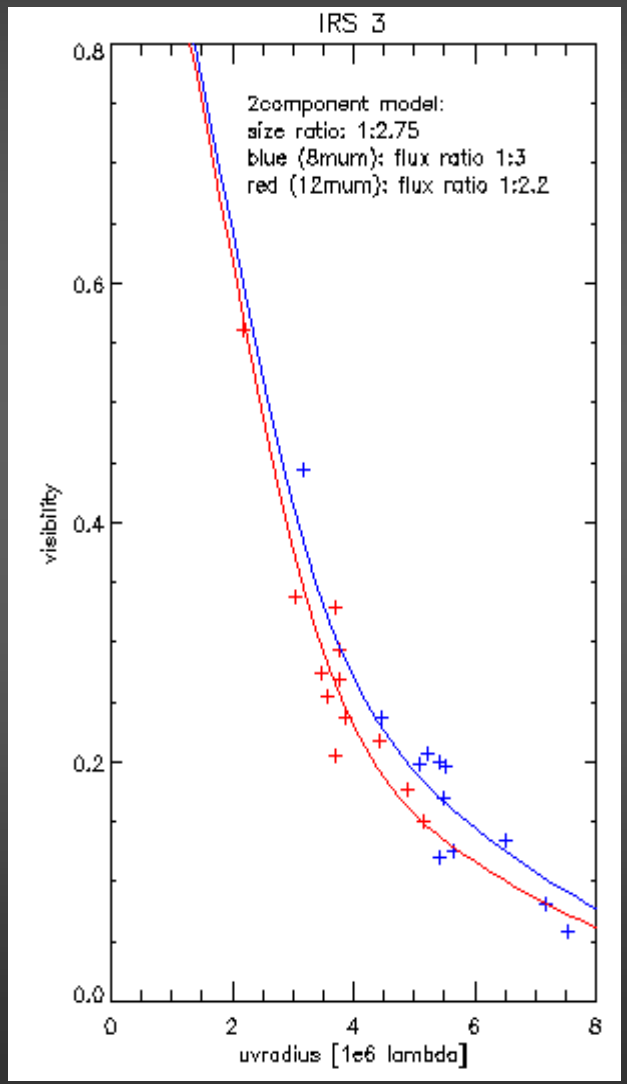
Please see also spring ESO Messanger:

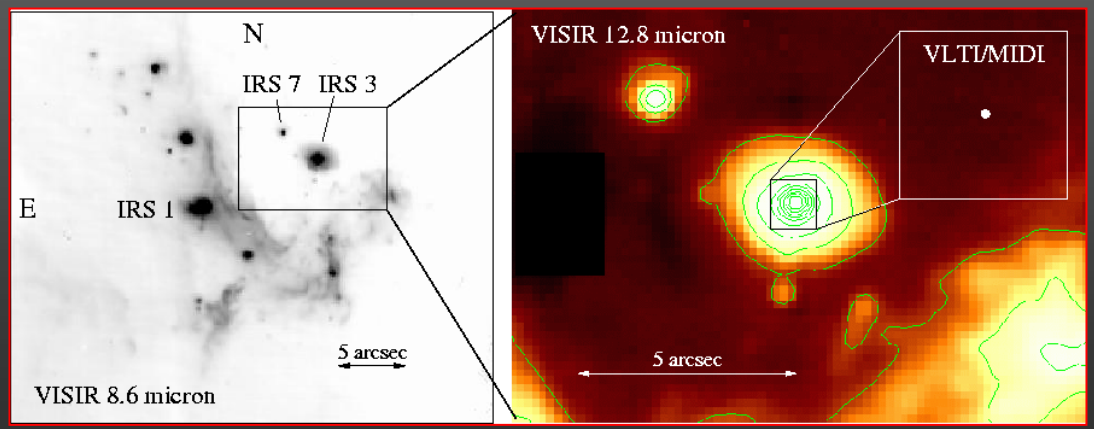
J.-U.Pott et al. : The brightest compact MIR source at the GC
VLTI Interferometric observations of IRS3



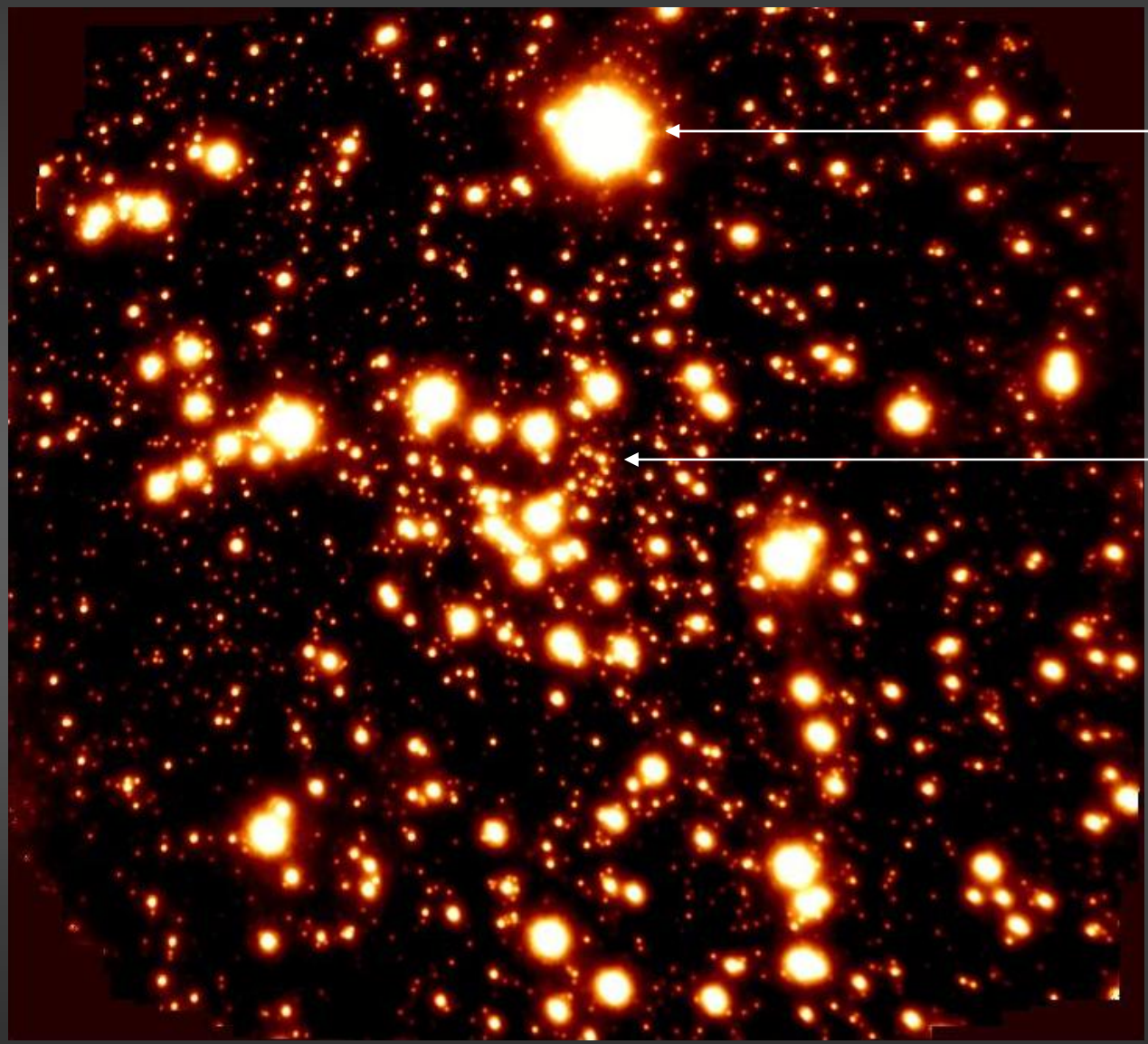
UT2-UT3 baseline 45m/30mas@10μm

UT1/UT2/UT3 baselines





Pott, Eckart et al. recently detected IRS7 with AMBER at the VLTI



NACO
NIR
2μm

The Galactic Center

For orbits in the 30mas to 100mas range orbital time scales are of the order of

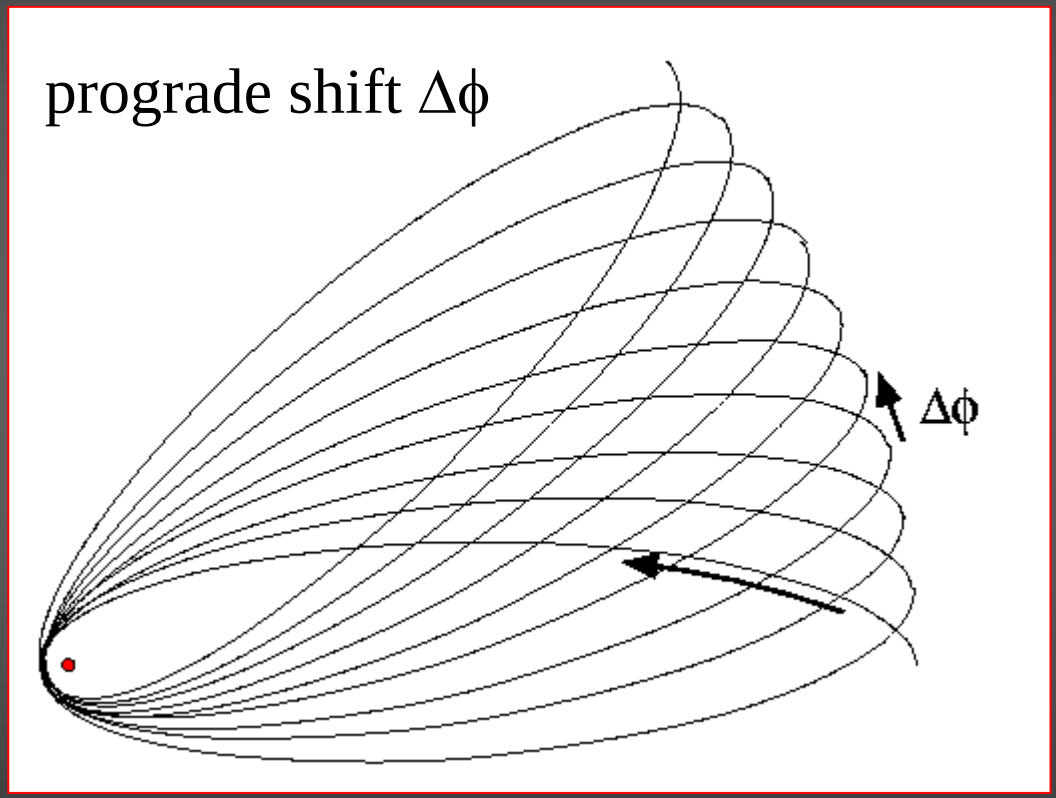
1 to 10 years.

Interferometry with a large FOV provides a large number of reference sources and exact measurements of positions and velocities.

Sources on close orbits allow to determine the compactness of the central mass.

Orbits

The Galactic Center



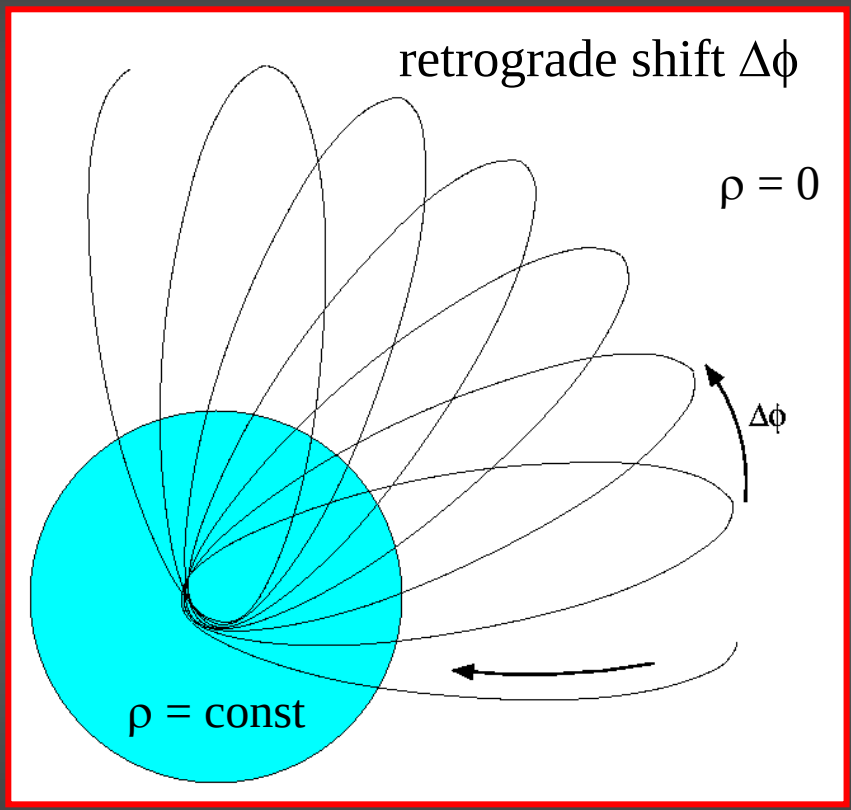
Relativistic periastron shift

$$\Delta\varphi = \frac{3\pi R_s}{a(1-\varepsilon^2)c^2}$$

with

$$R_s = \frac{2GM}{c^2}$$

The Galactic Center



Periastron shift due to an extended mass

$$\Delta\varphi = 2\arccos\left\{\frac{1}{e}\left(\frac{l^2}{GMR}-1\right)\right\}+\arcsin\left\{\frac{\frac{2}{R^2}-B}{\sqrt{B^2+4A}}\right\}-\frac{\pi}{2}$$

with

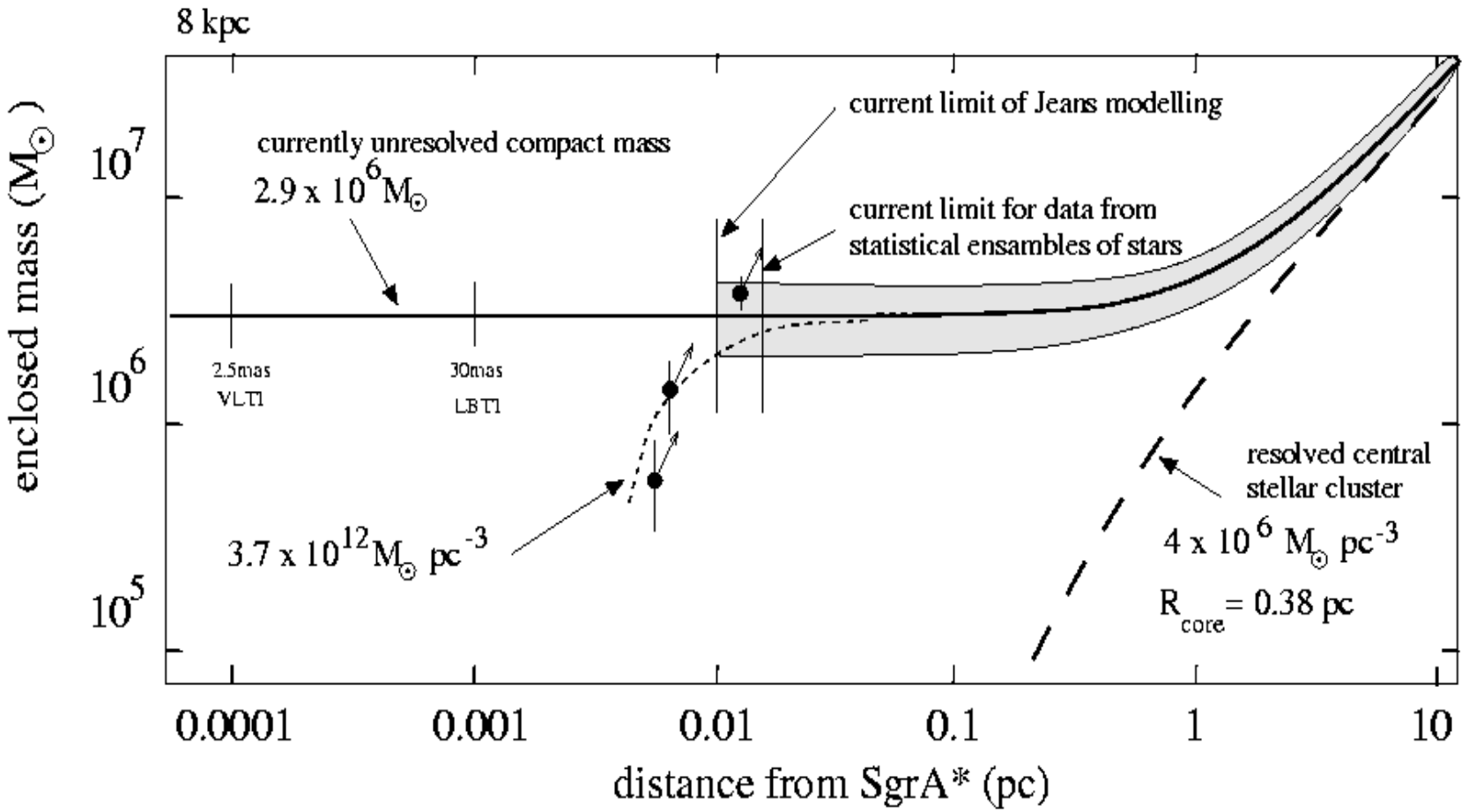
$$A=\frac{GM}{lR^3}$$

$$B=\frac{2E}{l^2}\left(1+\frac{3GM}{2RE}\right)$$

$$\vec{l}=\vec{r}\times\vec{v}$$

Jiang, H.X. and Lin, J.Y., 1985, Am.J.Phys., 53, 694

The Galactic Center



What fraction λ of mass is in the central compact mass ?

What fraction of mass could be extended?

Lensing

The Galactic Center

Tasks for Future Observations

- tracking stellar orbits (proper and radial m.)
- measure spectra of fast moving stars
- extending anisotropy tests to fainter magnitudes
- monitoring counter part of SgrA*
- finding and tracking sources near SgrA*
- determine periastron shifts and compactness of the central mass

GRAVITY
VLTI NIR/OPT Beam Combiner:
MPE, Paris, Cologne

Conclusion

The Galactic Center is a Massive Black Hole

Alternative scenarii become increasingly unlikely!

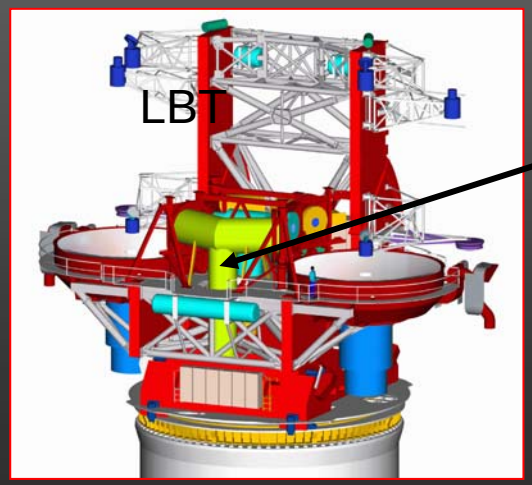
It is one of the best laboratories to study

fundamental physics

in the environment of large compact nuclear masses.

Inerferometric measurements in the radio and NIR/MIR combined with results from other wavelength domains

are ideally suited for future investigations



LINC/NIRVANA
LBT NIR/OPT Beam Combiner:
Universitity of Cologne
MPIA, Heidelberg
Osservatorio Astrofisico di Arcetri
MPIfR Bonn

UNIVERSITÄT ZU KÖLN

GC06
18-22 April 2006
Bad Honnef,Germany

(on the river Rhein, just south of Köln/Bonn)

End of Part II

End